HOUSEHOLD ADOPTION OF GREEN TECHNOLOGIES: THE CASE OF CHICAGO RAIN BARRELS

BY

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THESIS

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Part I. Introduction

1.1 Motivation and Research Question

The hydrological disruption caused by urban areas can be alleviated if households adopt water-friendly technologies such as rainwater harvesting technologies and low-flow plumbing fixtures. Government education and incentive programs can encourage households to make those choices, but no work has quantified how households will respond to such programs. This thesis seeks to identify the factors that influence household adoption of environmentally friendly stormwater management technologies.

To answer the research question, this analysis uses data from the City of Chicago's subsidized rain barrel program. It specifically explores factors such as transaction costs and public education campaigns to determine whether there are steps a city could take to increase the impact of a subsidized rain barrel program. It also tries to determine whether consumer adoption of rain barrels is significantly affected by consumers' experience of the aspect of environmental quality that the technology is intended to improve. This type of feedback is theoretically important to sustaining ecologically desirable levels of environmental quality (Liu et al. 2007).

To investigate hypotheses about green residential technology adoption, the analysis combines census and voting data for the Chicago area with spatial data that cover three years of adoptions from a city program that has run since 2004. It explores the spatial characteristics of rain barrel adoption, and uses econometric methods to evaluate the importance of socioeconomic and ideological factors in rain barrel adoption. The analysis then uses the econometric results to improve rain barrel distribution site selection.

Part two provides relevant background on the hydrologic benefits of rainwater harvesting and motivates the purpose and goals of Chicago's rain barrel program. Part three describes the origins and assembly of the data and explains the choice of econometric framework and variables as supported by economic literature. Part four provides a discussion of the regression results. Part five presents an extension that combines the regression results with techniques from optimization to improve green technology deployment and adoption. The study concludes with a discussion of the broader implications for the results.

Part II. Background

2.1 Effect of Urbanization on Hydrology

The problems that stem from urban modification to hydrologic landscapes are well understood. The need for housing, transportation, and other urban infrastructural amenities that arise from high population density in cities has usually resulted in the large scale construction of impervious surfaces. These alterations bring with them changes to the site's hydrological cycle that include decreased levels of water infiltration into the soil and modified patterns of surface and river runoff. New runoff patterns—intentional and otherwise—often create high peak stormwater flows, generate large volumes of runoff, and accelerate the transportation of pollutants and sediment from urban areas. Consequently, the hydrologic effects of urbanization are felt not only in the city, but also in the downstream river network (Niemczynowicz, 1999).

This radical modification of the hydrologic landscape contributes to undesirable outcomes not only in surface-water geomorphology, but also in regional climate, ecology, and riparian vegetation (White and Greer, 2006; Kinouchi and Miyamoto, 2007; Barco et al, 2008). The consequences that follow from the land use changes caused by urbanization have been studied in detail in various ecological contexts, including wetlands and urban streams (Wigmosta and Burges, 2001).

2.2 Water Supply Management Challenges for Chicago

The foregoing describes only the typical challenges a municipality faces with respect to stormwater. Chicago is extraordinary in that it faces two additional constraints. First, policymakers seek to promote water use conservation and efficiency with an eye to Illinois's ability to meet the northeastern region's future water needs. The Northeastern Illinois Planning Commission predicted in 2003 that the six-county Northeastern Illinois area will be home to an additional 1.94 million people by 2030. Among these, 1.16 million are predicted to live in areas that currently receive water from Lake Michigan (Office of Water Resources). While the Illinois Department of Natural Resources predicts this growth can be accommodated, it notes that its prediction is subject to uncertainty across many variables, and thus poses a risk Chicago must recognize in its water policy. The City must continue to observe the U.S. Supreme Court's 1967 decree (388 U.S. 426, 1967) and its 1980 amendment (449 U.S. 48, 1980) that limit the amount of water drawn from Lake Michigan by Illinois to 3,200 cubic feet per second. According to the Illinois Office of Water Resources, the state will be certified by the Army Corp. of Engineers by fall 2008 as having repaid its "water debt" as outlined by the decrees (Office of Water Resources, 2007). While Lake Michigan will be essential to servicing future water demand in northeastern Illinois, it may not be sufficient.

Second, the City must address combined sewer overflows that occur when stormwater exceeds its sewers' capacity. Overflows release untreated waste and stormwater into the Chicago River, sometimes causing basement floods in households. Chicago and USEPA have already invested in massive underground combined sewer overflow controls through the Tunnel and Reservoir Plan (TARP). Over 100 miles of 35 foot diameter tunnels currently help the City retain and treat stormwater runoff, but TARP only abates a portion of total overflows (Metropolitan Water Reclamation District of Greater Chicago, 1999). While TARP is a great downstream stormwater management system, it does little to manage stormwater at its highly decentralized source.

2.3 Chicago's Water Agenda

The plan to address these issues was presented by the City in its 2003 Water Agenda. This document outlines the three strategic aspects of water management that Chicago will target. The City will first promote conservation of its water resources, leading by example where possible. For instance, the City is reviewing its Building Code to more easily allow water-saving fixtures. Second, it will seek to protect water quality through policies that include increased monitoring and education. Third, it will attempt to better manage stormwater through the use of low impact development (LID) practices in addition to standard stormwater conveyance practices (Daley, 2003).

2.4 Low Impact Development

LID comprises a set of best management practices that attempts to harness ecologically sustainable development, and a major goal of LID is the maintenance or replication of a site's predevelopment hydrologic landscape (USEPA, 2000). Structures typically found in a LID design include grass swales, vegetated roof covers, permeable pavements, and rain gutter disconnects combined with rain barrels, among many others. These structures leave a developed site's hydrology functionally equivalent to its predevelopment state and preserve its ability to handle stormwater through infiltration rather than conveyance. LID technologies can thus contribute to all three of Chicago's Water Agenda goals. Furthermore, these technologies offer a decentralized and relatively much less capital intensive way to manage municipal stormwater. They can at times be deployed more cheaply or even at negative cost vis-à-vis comparable conveyance measures (Ando and Braden, 2008).

Among LID technologies is the rain barrel. Rain barrels promote conservation by allowing residents to harvest rainwater from rooftop gutter downspouts and therefore use water off the grid. Water collected from barrels is recommended for outdoor use, which generally encourages groundwater recharge (Department of Environment). In addition, because rain barrels prevent water from entering the sewer system during times of peak stormwater flows, they contribute to the prevention of combined sewer overflows. While rain barrels are available for retail in a variety of shapes and sizes, Chicago's rain barrel program offers a 50-gallon, recycled food-grade plastic barrel. The barrels typically retail for about $80, but the city subsidizes a substantial part of the cost. The barrel comes in one of three colors, is mosquito-proofed, and includes a spigot (City of Chicago). Residents are allowed to purchase one subsidized barrel per household per year. Along with the subsidy, the City has actively advertised rain barrels as a way for residents to become directly involved in stormwater management.

2.5 Rainwater Harvesting in the U.S. and Abroad

The effectiveness of municipal rain barrel programs in the United States is in general not well documented. This contrasts with the Australian and Swedish experiences, where studies have shown that trickle-fed rainwater tanks with greater capacity and broader water usage possibilities can make significant contributions to both municipal water supply and stormwater management. The use of 5,000 – 15,000 liter (1,321-3,963 gallon) tanks in residences can provide potable-quality water that can serve in toilet, hot water, and outdoor uses, and delay construction of new dams by up to 34 years (Coombes and Kuczera, 2002). A case study of household rainwater harvesting in Australia provides additional evidence of its benefits:

> "Monitoring of the performance (during a 169 day period) of the dual water supply system at the Maryville house [in the suburb of Newcastle in New South Wales] revealed that use of the rainwater tank reduced stormwater volumetric (36%) and peak discharges (86%), and mains water peak daily (80%), peak instantaneous (94%) and volumetric (52%) demands. The widespread installation of rainwater tanks is likely to significantly reduce the requirement for new dams, water supply and stormwater drainage infrastructure (Coombes, Kuczera, and Kalma, 2002)."

Residential rainwater tanks between 1,000-5,000 liters (264-1,321 gallons) generated the greatest water savings in urban settings, with 5,000 liters being closest to optimal, and provided a method for harvesting rain during drought periods (Coombes and Kuczera, 2003a). In Sweden, a study considering the effects of water-saving measures found that the use of two 40,000 – 80,000 liter (10,566-21,134 gallon) rainwater tanks supplying 1100 apartments could generate substantial water savings.

The only report that rigorously studies the cost effectiveness of American rainwater harvesting suggests that, at least as they are currently employed, rain barrels can produce substantial water savings but not cost savings (Trieu et al, 2001). Evidence from abroad suggests that residential rainwater harvesting can produce cost savings if properly deployed. Coombes et al. (2002) performs a detailed analysis of potential cost savings from rainwater harvesting and conservatively estimates that an urban population of about 450,000 can save AUS$67 million (US$46.2 million) in net present value from the use of rainwater tanks. Importantly, this valuation does not include environmental benefits associated with the positive externalities of delayed dam construction, reductions in peak demand, and avoided sewer overflows from reduced peak stormwater flows. A sensitivity analysis of these results shows that this is true for a broad range of assumed parameters (Coombes and Kuczera, 2003b). A case study of residence-level rainwater harvesting finds that (at least in that particular case) a household can lower its cost of water supply by relying mainly on rainwater (Coombes, Kuczera, and Kalma, 2002).

The divergence in cost effectiveness between the U.S. and Europe likely stems from differences in tank volumes and setup. The smallest tank analyzed in Australia is over five times as large as barrels distributed by Chicago and over four times as large as barrels used in Trieu (2001). The volume constraint and rudimentary setup limit the possible applications for rainwater. In Chicago, rainwater is generally recommended for outdoor use, while Australians are able to use their water for drinking, hot water, toilet, laundry, and outdoor uses. In addition, because rainwater tanks are deployed as a centerpiece of domestic water provision in Australia, rainwater from tanks is only complemented by mains water. This prioritizes use of harvested water and limits consumption from the municipal grid to the purpose of maintaining a minimum water level in the tank (Coombes, Kuczera, and Kalma, 2002; Coombes and Kuczera 2003a). Nevertheless, even if the usual scale of deployment is not as large for municipalities in the U.S. as it is in other countries, private water savings and positive externalities in terms of reduced peak water flows and groundwater recharge still accrue.

2.6 Chicago's Rain Barrel Program

Chicago's Rain Barrel Program has existed since 2004. Table 1, reproduced from the "Rain Barrel Summary Report," shows overall patterns in adoptions and subsidies. Adoptions have grown year-on-year, though at a decreasing rate. The subsidy provided by Chicago has also fallen over time. In 2005, the City did not provide subsidies for rain barrels, but instead encouraged outdoor supply businesses to market them. The result was a trivial number of adoptions and no records (Department of Environment). The City's records show that about 3,850 subsidized barrels had been sold by the end of 2007. The data for this study comprise a subset of 2,773 addresses. The source of the discrepancy between number of addresses and estimates of barrel sold is not known; however, each yearly subset represents 56-79% of the reported yearly sales. While a few of the sales records show some rain barrel purchases were for more than one barrel, the vast majority of purchases were for a single barrel. This analysis assumes that one barrel per reported address is purchased. Of course, privately purchased, unsubsidized rain barrels are not included in this analysis. However, if the 2005 evidence is any indication, unsubsidized purchase rates are very small.

The Rain Barrel Program is overseen by the Chicago Department of Environment and is based out of the Chicago Center for Green Technology. Distribution has been handled differently over the three years studied. In 2004, the distribution method was neighborhood-oriented, with one-time events held in six different neighborhoods. Local retailers sold barrels at market price in 2005, which resulted in few sales and no record of sales. DOE resumed management of distribution in 2006, hosting six one-day events and accepting walk-ins for the first two months of fall. In 2007, the Program switched from one-day events to walk-ins, with four gardening retailers and the Chicago Center for Green Technology selling them during regular hours for the entire summer (Department of Environment).

Part III. Data and Econometric Framework

3.1 Framework for Variable Choice

Several factors are proposed to affect the adoption of rain barrels. Median household income ought to have some positive influence on adoption propensity due to the discretionary nature of the purchase. Conventional models of consumer choice indicate that price and income should play a role in determining whether households choose to buy a product like a rain barrel. High income and low price should stimulate adoption. Ashraf, Berry and Shapiro (2007) come to two conclusions: households are not less likely to use an unfamiliar product if it is given away for free, but a higher price creates a mix of buyers that are more likely to use a product.[2] Median age controls for the possibility that a particular age group is more receptive to "green" environmental practices. Higher levels of education may positively affect receptiveness to environmental sustainability programs, as Nelson, Uwasu, and Polasky (2007) find in a study of open space conservation in the U.S.; thus, the analysis includes the fraction of residents who hold at least a bachelor's degree.

The adoption of rain barrels fits the framework of recent economic literature that attempts to explain trends in "green," or environmentally motivated, consumer choice. Nyborg et al. (2006) point out that it is consistent with economic models to assume that contributions to public goods can also produce private benefits, so-called "warm glow." Kotchen and Moore (2008) study premium-priced renewable power purchases in Traverse City, Michigan and find that "conservationist" consumers are willing to pay more for green power and consume less in the absence of such a program. Kahn (2007) finds that residents of areas with higher Green Party membership are more likely to walk to work; have shorter commutes; not own private vehicles; and own hybrid versions of vehicles, perhaps as a visible commitment to environmentalism. In general, he finds that Green Party registration is a good proxy for political ideology. This study uses voting for the Green candidate in the 2006 gubernatorial election in an attempt to capture similar

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[2] The product in this case is a home water filtration system offered to households in Zambia.

effects; in particular, tracts with higher fractions of residents who vote for the Green party candidate are theoretically more likely to adopt barrels.

Issues of convenience and transaction costs may also affect green technology adoption. For example, a recent study of recycling in multifamily dwellings shows that transaction costs in the form of storage space and distance to bins are significant factors in determining recycling program participation (Ando and Gosselin, 2005). Because barrels are quite large and difficult to transport without a car, fraction of households without a vehicle and average distance from a distribution location are included.

These data offer an opportunity to test whether consumer adoption of green technology is significantly affected by changes in the aspects of environmental quality that the technology is intended to improve. This interaction between human behavior and environmental quality is said to be important to the maintenance of desirable, sustainable ecological conditions over time (Liu et al. 2007). The City has promoted rain barrels as a way to locally combat residential basement floods (Department of Environment, 2007). The average number of basement flooding events over the three years is included to test the hypothesis of an environmental feedback mechanism between flooding and barrel ownership. The effect is supposed to be lagged, such that the previous year's flooding affect the current year's adoption.

The binary variable for Green Alleys is included to investigate whether educational campaigns have the desired effect. Previous research has shown these campaigns to be statistically significant in swaying adopters. Craig et al. (2007) shows that a national Canadian campaign to promote pedometer use and walking has a significant effect and can promote positive health outcomes. Researchers in the Netherlands shows how a Dutch health promotion campaign significantly reduces travel-related mortality among members of an ethnic minority group (Uitenbroek et al, 2000). Menanteau and Lefebvre's (2000) case study of the compact fluorescent light bulb suggests that public programs may play an important role in providing niche technologies the space they need to flourish in the market place.

Variability in housing type and arrangement must be carefully considered, especially since certain structures are more amenable to rain barrel installation and use. A higher number of occupied housing units should generally lead to a greater number of barrel purchases. Further, a higher number of owner-occupied units should positively influence the probability a tract has any barrels, as owner-occupiers have greater incentives to make long-term investments. From a principal-agent standpoint, one might expect renters to be less likely to invest in longer term, housing-related infrastructure, though Gatzlaff, Green and Ling (1998) do not find evidence of such bias. Housing stock composition also ought to have some effect on adoption. Multi-unit structures are likely to have less outdoor space for rain barrels, while single-unit structures are more likely to have a yard that can accommodate the device. Thus, proportion of housing stock in structures with 10 or more units and proportion of housing stock in single-unit structures are both included in the analysis.

3.2 Sources

To test hypotheses regarding rain barrel adoption, the analysis draws upon data from several sources and relies on geographic information systems (GIS) tools for variable construction. Most of the data manipulation is performed using ESRI ArcMap. The projected coordinate system used is UTM Zone 16N, and the geographic coordinate system is WGS 1984**.** The unit of observation is the census tract for three reasons. First, many of the explanatory variables are already aggregated at that level. Second, while the analysis would ideally be performed at the household level, no such data are available. Third, there is sufficient variability in the variables at the tract level to provide a meaningful analysis of rain barrel adoption. This can be seen in Figures 1 through 16, which illustrate the geography of the variables.

Table 1 provides descriptions of the data and their sources. Census tract-level demographic data comes from the U.S. Decennial Census 2000. This includes the data on median age, number of housing units occupied, number of housing units occupied by their owners, median household income, fraction of housing stock comprised of attached or detached single-unit structures, fraction of housing stock comprised of buildings of ten or more (henceforth multifamily) residential units, fraction of population 25 years or older with at least a bachelor's degree, and fraction of households without a car.

A number of data were made available by the City, including an ESRI shape file of the census tracts that comprise Chicago. Addresses for rain barrel buyers were provided at the household level. Household level basement flooding data are collected from Chicago's 311 City Service call-in program, which provides residents an easy way to file police reports or other complaints. The basement flooding data include all reports of "water in basement" for 2003, 2005, and 2006, the years immediately preceding the three years during which the city sold subsidized rain barrels. Green Alley locations until March 2008 were given as the streets that bound the Alley. Lastly, locations where rain barrel distribution occurred were provided as addresses. These include all one-day event and walk-in locations for the years studied.

The data were assembled in several steps using ESRI ArcMap and ArcCatalog. Wherever required, geocoding of addresses was performed using http://www.batchgeocode.com/. Census information for Dupage and Cook counties, where Chicago is located, was joined to the shape file based on census tract numbers to ensure accuracy. Of those 876 tracts, 13 were dropped due to zero housing occupancy. The remaining tracts have at least one occupied housing unit, an important requirement for a valid observation.

Election data for the 2006 gubernatorial vote were obtained at the precinct level for each of Chicago's 50 wards.[3] There is no geographic congruence between city wards and census tracts, as seen in Figure 1. To create tract-level voting variables, each of the Democratic, Republican, and Green party votes were turned into rasters and aggregated

[3] These are publicly available data found at http://www.chicagoelections.com/ and reflect votes for the Democratic, Republican, and Green parties. Data on the geography of Chicago's wards were obtained from http://www.cityofchicago.org/gis in ESRI shape file format, which provides a GIS rendition of the data.

by census tract using ArcMap's *Zonal Statistics by Table* tool. Precincts were aggregated into tracts using proportional area as the aggregation weight.

The two dependent variables used in the analysis are a count of rain barrels per tract and a binary variable that equals one if a tract has at least one barrel and zero otherwise. The former was geocoded and obtained using a spatial join operation in ArcMap. The latter was generated using STATA.

Basement flooding data are used to create a variable that averages water-in-basement occurrences over years 2003, 2005, and 2006. Since flood instances were given as points, a spatial join was performed in ArcMap to count the number of points in each tract.

The Green Alleys data were used to generate a binary variable to indicate if a tract intersects at least one Green Alley. Because of the relatively small number of Green Alleys, a binary variable rather than a count was used. The shape file for Green Alleys was generated manually using ArcCatalog and ArcMap. Google Maps was used to find the intersections of the streets which bound the Alleys; the intersections were then geocoded, entered as points in a shape file, and connected. This was intersected with census tracts to determine which tracts contained part of at least one Alley.

Lastly, distribution points and census tracts addresses were used to construct a variable that measures the average linear distance between a census tract and the closest distribution point over the three years. To simplify matters, “event” distribution points and longer term “walk-in” distribution points are not differentiated; all distribution points are considered to be the same. Rather than using rain barrel buyers' addresses as one endpoint for the distance measurement, the distance calculation uses the centroid (area-weighted center) of the census tract. Using the tract’s centroid creates an exogenous variable, whereas distance between distribution location and adoption point generates a variable that is endogenous. Distances are computed as a straight line between a tract's centroid and the nearest distribution point available that year using Hawth's Tools, a GIS spatial ecology package for ArcMap. The three years' distances are averaged to create an overall average distance.

3.3 Summary Statistics and Maps

Table 2 provides descriptions of the variables, and Table 3 provides summary statistics on the data. In the 863 census tracts that comprise the sample, about 63% have at least one rain barrel purchased from the city program, and the number of barrels per tract ranges from zero to 48. Housing composition varies widely in the city; on average, census tracts have housing stock composition of 29.69% in single-unit structures and 21.70% in structures with ten or more units. The mean fraction of households in a tract that do not own a car is about 30.29% and varies from zero to 100%. The yearly average number of reported basement floods has a mean of 7.71 (with a median of 4), but the standard deviation is 10.8 due to wide variation in flooding conditions around the city. Finally, only 4.4% of census tracts intersect Green Alleys at all.

Figure 2 illustrates the spatial dispersion of rain barrels throughout the city. The Moran's I statistic, an indicator of overall spatial autocorrelation, is positive (0.4913) and significant for the whole city, providing evidence of positive spatial clustering at a global scale. Figure 3 shows a local index of spatial association (LISA) map, which serves to identify positive or negative autocorrelation for individual tracts (Anselin 1995). Figure 3 shows areas where tracts with relatively large values of rain barrel adoption are surrounded by other tracts with similarly high number of adoptions; a similar result holds for low adoption tracts. Evidence from the figure indicates that there is clustering among observations that is not captured by Moran's I.

It is not obvious that the observed pattern results from any particular phenomenon. Similar patterns could arise from positive social interaction effects, sorting in residential location choice, or spatially autocorrelated explanatory factors otherwise uncontrolled in the data. Spatial econometric techniques that incorporate spatial autocorrelation across the landscape will be used to ensure that the spatial autocorrelation seen here does not seriously bias the resultant coefficient estimates.

The geographical dispersion of each variable is displayed in various figures in Appendix A. Among the notable figures are Figure 2, a map of rain barrel adoption by tract; Figure 5, which shows proportion of votes for the Green Party candidate; Figure 9, a map of median household income; and Figure 14, which shows the average distance from tract centroids to the nearest rain barrel distribution point. The remaining variables are similarly illustrated in Figures 4 through 16.

3.4 Econometric Specification

The data described in Section 3.2 allow for the opportunity to test which relationships among those hypothesized in Section 3.1 are statistically significant. The structure of the data offers the possibility for estimating two outcomes. One may estimate the number of rain barrels adopted in a given census tract. In addition, because of the relatively low mean of 3.21 barrels per tract, it seems appropriate to estimate the probability of observing at least one barrel in a particular tract. These goals make inadequate the standard approach of ordinary least squares regression for two reasons. First, in estimating the number of rain barrels, adoption must be positive in all tracts. This means that an appropriate model ought to be analytically bounded at zero. Second, when estimating the probability of adoption, no tract can have a negative probability of adoption. To avoid these potential pitfalls, two general types of regressions are implemented: logit and negative binomial (NB).

These regression models are well understood in the applied economics literature. A logit regression is estimated to find the probability of adoption per tract. The estimate is functionally constrained to the interval [0,1], which rules out probabilities that are negative or greater than unity. For this specification, a binary variable Y that equals one if there is at least one barrel, zero otherwise, is regressed on set of independent variables found in Table 2. The logit model is based on the logistic distribution, and the regression chooses parameters to maximize its likelihood function. The logit regression estimates

$$\text{Prob}[Y=1]=\frac{\exp(\beta' x)}{1+\exp(\beta' x)}=\Lambda(\beta' x) \tag{1}$$

where Λ represents the logistic cumulative distribution function. The probability model is a binary regression given by

$$E[y]=0[1-\Lambda(\beta' x)]+1[\Lambda(\beta' x)]=\Lambda(\beta' x) \tag{2}$$

To estimate the number of barrels adopted per tract, this study implements a NB regression. In this framework, the dependent variable is a count of the number of barrels that were adopted in a census tract over all years considered in this study. The most important feature of the NB specification is that it is functionally bounded at zero, disallowing negative estimates of adoption. The NB regression is used instead of the simpler Poisson count model because it relaxes the latter's assumption of equal mean and variance of the process.[4] According to the statistics in Table 3**,** the data display overdispersion (i.e. mean not equal to the variance). The results of the NB analysis are used to evaluate the impact of an explanatory variable on the expected number of rain barrels that will be adopted in a tract.

The negative binomial distribution is described in Cameron and Trivedi (1986). This count model is given by

$$\begin{aligned}\text{Prob}[Y_i=y_i] &= \int \text{Prob}[Y_i=y_i]\, f(\lambda_i)\mathrm{d}\lambda_i \\ &= \frac{\Gamma(y_i+\nu_i)}{\Gamma(y_i+1)\Gamma(\nu_i)}\left(\frac{\nu_i}{\nu_i+\phi_i}\right)^{\nu_i}\left(\frac{\phi_i}{\nu_i+\phi_i}\right)^{y_i}\end{aligned} \tag{3}$$

where

$$f(\lambda_i)=\frac{1}{\Gamma(v_i)}\left(\frac{v_i\lambda_i}{\phi_i}\right)\exp\left(\frac{-v_i\lambda_i}{\phi_i}\right)\frac{1}{\lambda_i} \tag{4}$$

$$\lambda_i=\exp(\beta' x) \tag{5}$$

$$\lambda_i \sim \Gamma(\phi_i, v_i) \tag{6}$$

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4 Specifically, I employ the negative binomial specification that uses a constant dispersion parameter. Choice of dispersion form (mean vs. constant) does not significantly alter results.

The use of two models is instructive in establishing the robustness of inferences. All else equal, results that match in sign and significance across multiple models are more credible than those that do not.

A special concern that must be addressed is that of possible spatial autocorrelation among the observations. The context of the data in this study suggests two processes by which spatial autocorrelation may occur. The first is residential sorting, first articulated by Tiebout (1956), who argued that consumer-voters would choose to live in areas where others shared their preferences for public goods provision. Under Tiebout's model, communities will naturally sort themselves such that each provides the optimal level of public goods and associated taxation for its residents. Evidence of residential sorting arises in many contexts. Kahn (2007) finds that areas with higher Green Party membership are more likely to rely on public transportation, which is reflected in the spatial clustering of Greens. This compares well with the findings of Waldfogel (2006), who shows that this is generally the case with certain private amenities like restaurants. Pinjari et al. (2007) show that built environment significantly affects individuals' housing decisions, and that changes to the environment may affect people's choices; for example, households that locate in areas that have more facilities amenable to cyclists tend to own more bicycles. It is possible that consumers who are prone to adopt barrels do so as part of a bundle of other choices and choose to live with others who share their tastes.

The second process is knowledge diffusion, which entails the possibility that residents who adopt rain barrels may affect the adoption odds of their neighbors. The economic literature on learning and knowledge diffusion indicates that it can be an important phenomenon. Foster and Rosenzweig (1995) study household level data from rural India and find that imperfect knowledge about a new crop seed variety constitutes a significant barrier to the technology's adoption in the market. The authors find evidence of knowledge spillovers and farmers' tendency to free ride on each others' knowledge. Bandiera and Rasul (2006) study new crop adoption in northern Mozambique and find that individuals with better information are less sensitive to the opinions of those around them, while those with stronger social ties are more likely to be affected by their neighbors' decisions. Kapur (1995) provides a complementary theoretical framework for considering the adoption of a new technology. The author shows that adoption may be treated as a waiting contest where firms weigh the payoff (or loss) from adopting now against the additional information gained from waiting and watching others adopt.

Spatial sorting and knowledge diffusion can each be addressed through the use of spatial econometric models that explicitly incorporate spatial dependence among variables or outcomes (Anselin 1988, 1999). The observed location of each rain barrel may depend upon the location of other rain barrels, as in knowledge diffusion, or a factor that is uncontrolled in the regression and is correlated across space, as in residential sorting. To control for autocorrelation between observed outcomes, a spatial lag regression model is used. This model is often expressed as

$$y = \rho W y + \beta x + e \tag{7}$$

where W is a weight matrix that explicitly defines the spatial relationship between observation, rho is a parameter of the regression that expresses the degree to which observations depend upon one another, β is a vector of coefficient estimates, and x is a vector of data values.

In a separate regression, a spatial error model is estimated. This is commonly written

$$y = \beta x + e, \quad e = \lambda W e + u \tag{8}$$

where W, β, and x are as above, lambda is a parameter that captures the spatial heterogeneity in the error term, e is an error term that is spatially autocorrelated, and u is a normally distributed error term.

Although both regressions include an explicit model of the spatial factors that affect an observed outcome, their interpretations are quite different. In the spatial lag model, observed outcomes depend to some extent (captured by rho) on the outcomes of their neighbors. In the context of rain barrels, one could consider this the learning process: as more residents in an area purchase barrels, their neighbors become aware of the associated benefits and become more likely to make their own purchases. In the spatial error model, it is not observed outcomes that are affected by their neighbors, but rather their associated errors. There is heterogeneity across the landscape that is not reflected in the model's specification, but which causes spatially correlated heteroskedasticity (captured by lambda) in the error term. This is more conducive to a residential sorting story: there exist characteristics about the residents in areas where barrels are adopted which are not present in the model, but which manifest themselves in the observed pattern of rain barrel adoptions.

The spatial lag model carries with it one important caveat. The theoretical underpinnings of the model are designed to generate estimate of spatial influence between neighboring households. The kinds of learning interactions proposed above occur chiefly at the household, but are aggregated at a spatial resolution that that can include thousands of households. As a consequence, the degree of spatial interdependence is very likely to be understated, if at all. This should be kept in mind when considering the model's output.

To estimate the effects of spatial autocorrelation among the observations, this analysis follows Albers et al. (2008) in employing the Markov chain Monte Carlo Gibbs Sampler method. The code and instructions for implementing a spatial logit are part of James LeSage's *Econometrics Toolbox*, which is a publicly available set of MATLAB scripts (LeSage, 2009). The method uses a first-order queen contiguity weight matrix to allow adjacent tracts to influence (and be influenced by) each other's adoption levels.[5] The implementation draws 15,000 samples and omits the first 500 to allow for adequate convergence in parameter estimates.

[5] Estimates were also generated using a rook contiguity weight matrix, but results were qualitatively equivalent to the queen contiguity matrix.

Part IV. Econometric Results

4.1 Regression Results

Table 4 presents the results for each regression specification. These will be discussed below in three sections: specifications without ward dummies; specifications with ward dummies; and specifications that explicitly account for spatial factors rather than employing ward dummies.

4.2 Regressions without Ward Dummies

Results for both the logit and NB regressions without dummies are broadly consistent with theoretical relationships proposed. Median age is not robust to both models, although it is highly significant and positive in the NB case. Fraction of residents who vote Republican does not seem to matter for adoption, but proportion of residents who vote for the Green party candidate is highly significant for both models. Both the linear and the quadratic income terms have the expected signs (positive and negative, respectively), but the quadratic term is not robust to the logit. Proportion of population with at least a bachelor's degree has a negative and significant effect, which is very counterintuitive. A possible cause for such an outcome might be a high degree of multicollinearity between education and income, which has a value of 0.69.

Housing occupancy is positive and significant across both models, as expected, but owner occupancy is insignificant. While proportion of housing stock in single-unit dwellings is significant and positive only in the NB, proportion of housing stock in multifamily structures is negative and highly significant across both logit and NB specifications.

Car ownership does not seem to matter, although average distance to nearest distribution center is negative and significant. Basement flooding and Green Alleys are insignificant in both specifications.

4.3 Regressions with Ward Dummies

Results for both the logit and NB regressions with dummies are also broadly consistent with the sign relationships proposed earlier. One important item to note is that five wards are fully dropped from the logit model because their dummies perfectly determine the outcomes in those tracts. These were wards 19, 33, 39, 43, 45, 47, and 49; sixty-seven observations are lost, leaving 773 valid observations in the sample.

In general, there is agreement between the results of the no-dummy regressions and those of the regressions with dummies. Median age no longer matters to adoption. Republican voting remains insignificant, and votes for the Green candidate continue to be strongly significant and positive. Both income variables remain the same in sign and significance, while education loses significance in the both models.

Number of housing units occupied is still positive and significant, while owner occupancy shows the expected positive sign and significance in the NB model. The estimates for dwelling type change slightly: proportion of single-unit housing stock is positive but no longer a good predictor of rain barrel adoption, while fraction of housing in multifamily structures is still negative and highly significant.

After controlling for ward differences, car non-ownership becomes positive and significant in the logit. This finding defies expectations, but may present an alternative sort of preference for environmental quality: residents may shun cars as a way to lead lower impact lifestyles. Average distance to nearest distribution center remains highly important and negative in the NB model, but loses significance in the logit framework. Basement flooding remains insignificant and agrees with the no-dummy model. Green Alleys positively influence the number of barrels adopted, but not the odds of observing at least one barrel.

In summary, number of units occupied, voting for the Green candidate, income, and proportion of housing stock as multifamily dwellings are robust to all four specifications, and average distance to a distribution center is robust to three of the four.

Green Alleys and single-unit structures are each robust to one of the NB specifications but to neither of the logit models. The remaining variables are not well suited to generalizations and offer mixed or non-robust results.

4.4 Spatial Econometric Specifications

As previously discussed, spatial regression specifications explicitly model spatial characteristics of the data. In the spatial autoregressive model (SARM), observations are assumed to be functions not only of the independent variables, but also of the outcomes observed by their neighbors. In the spatial error model (SEM), heterogeneity not captured by the independent variables is present in the error term, which is then modeled to be affected by the outcomes of error terms of adjacent observations.

Table 5 reports the results of the spatial regressions. In terms of variables signs and significance, the SARM and SEM are identical. Lambda, the measure of heteroskedasticity in the error term for the SEM, is positive and insignificant. The measure of spatial autocorrelation in the SARM is also positive and insignificant. These models offer a few conclusions. Knowledge diffusion, as in the SARM, does not appear to be present given an insignificant coefficient of spatial autocorrelation. In addition, there does not appear to be evidence from the SEM that residential sorting is the mechanism that drives adoption patterns. It is possible that variables like voting capture the same heterogeneity that the SEM seeks to control.

The independent variables for both spatial models are the same in sign and significance as the logit with dummies. The only differences are in the SARM, where proportion of single-unit structures is not significant. Median age, owner occupancy, Republican voting, car ownership, basement flooding, and Green Alleys are each insignificant. Number of housing units occupied is positive, and proportion of multifamily structures still bears a negative sign. Green voting remains a positive factor affecting adoption, and incomes' linear and quadratic terms continue to be positive and negative, respectively. Education continues to show an unexpected negative and significant coefficient. Average distance to nearest distribution center is negative, while basement flooding and Green Alleys are each insignificant.

4.5 Marginal Effects

To investigate the effect on rain barrel adoption of small changes in the dependent variables, the analysis will use the results of the logit and NB models without dummies. Similar results should hold for the regressions that control for ward heterogeneity as the coefficient estimates are quite close for each regression type. Because both logit and NB specifications are nonlinear, one cannot take the reported coefficients to be the marginal effects. In general, the marginal effect for each regression is given by

$$\frac{\partial \Pr ob[Y_i = y_i]}{dx} \tag{9}$$

Logit marginal effects represent changes in the probability of adoption given a small change in an independent variable and are given by

$$\frac{\partial E[y]}{\partial x} = \Lambda(\beta' x)(1 - \Lambda(\beta' x))\beta \text{ , } \Lambda(\beta' x) = \frac{e^{\beta' x}}{1 + e^{\beta' x}} \tag{10}$$

Negative binomial marginal effects represent a change in the expected count of adoptions given a small change in the independent variable. Both marginal effects were estimated using STATA.

Marginal effects are typically calculated in one of two ways. One method finds the mean value for each variable and uses those as the *x* vector values in the above equations. The second method finds the marginal effect for each observation and takes the mean effect of those outcomes. The calculations produce results that converge in the limit, but finite samples can exhibit some divergence.

Table 6 presents marginal effects derived by taking the mean effect across all observations using the no-dummy logit and NB specifications. The marginal changes themselves are obtained by setting all other independent variables to their means and computing the change in the outcome from a small change in the independent variable of interest. Using marginal effects to predict outcomes, the average tract has a 70.5% chance of containing at least one barrel and, on average, each tract has 1.62 barrels. Table 8 tabulates predicted versus observed outcomes in the logit, and Figure 17 displays the predicted values of the negative binomial versus observed outcomes.

These predictions, while interesting, are more informative when placed into context. A more enlightening use of these results is presented in Table 7, which lays out some useful scenarios to explore certain aspects of the data. A shift of 10 percentage points in median housing make-up (proportion of multifamily structures increases from 9.6% to 19.6% and proportion of single-unit structures decreases from 20.2% to 10.2%) produces on average a -3.9% change in the odds of observing at least one barrel, and 0.55 fewer barrels per tract. An increase of $10,000 in median household income increases the probability of observing at least one barrel by 6.9% and the number of barrels by 0.51. If the City could bring a distribution point to one mile from a tract rather than the average distance of 4.1 miles, the odds of one or more adoptions would increase by 8.0% and additional adoption would number 1.97 barrels per tract; if the City delivered barrels to residents, odds would increase to 10.5% and adoption would increase by 2.87 barrels per tract. Finally, the existence of a Green Alley increases the number of barrels in the tract by 0.55, but does not produce a (significant) higher probability of adoption.

4.6 Discussion of Results

The body of regression results suggests several general conclusions. Ward dummies are indeed significant, as shown by the *F* test for joint insignificance of all dummies in Table 4. However, the character of most of the results remains unchanged when comparing the no-dummy against dummy regressions. Further, a comparison of the three logit models reveals only a few qualitative discrepancies among the estimates. In the SEM, the measure of spatial autocorrelation in the error term is insignificant. This evidence suggests that there exists sufficient spatial heterogeneity for the ward dummies to capture, but not in a way that yields systematic autocorrelation in the error term.

Many of the results are robust across all models. A larger number of occupied residential units in a tract implies a greater number and likelihood of adoptions. Income plays an important role in determining rain barrel adoption: higher income tracts tend to have more barrels, but gains exhibit decreasing returns. Tracts with higher proportions of their populations living in multifamily dwellings have fewer barrels on average. Political ideology provides a good proxy for capturing a preference for costly, environmentally friendly practices: Green Party voting explains adoption well, while the insignificance of Republican voting signals that voters who choose Republicans and Democrats have similar preferences toward rain barrels.

Basement flooding is not shown to be a significant factor in determining adoption, which may be due to two reasons. One is that the stormwater control benefits provided by rain barrels are simply too small to matter and thus do not affect adoption. Another is that consumers do not approach rain barrels as a tool to combat basement flooding, perhaps opting for other alternatives. Green Alley presence was significant in only one NB model. It is remarkable that any significance was obtained at all; a very small number of observations intersect Green Alleys. The evidence suggests that Alleys are important to adoption, though additional research would be required for a firm answer.

Several results did not yield the expected effect on adoption. Median age and proportion of single-unit structure are significant and signed as proposed but are not robust across specifications. Owner occupancy, which was suggested to affect adoption in a positive manner, does not deliver a conclusive result. Education has a consistently negative coefficient in the regressions, but this may be due to its high correlation with income. After controlling for possible ward heterogeneity, proportion of residents without a personal vehicle exhibits a positive effect on adoption. This outcome may signal a different kind of environmentally friendly living than previously thought: rain barrel ownership and car non-ownership are compatible if considered as part of a bundle of environmentally friendly lifestyle choices.

Average distance to nearest distribution location was robust to three of the four models and, as previously discussed, produces a large marginal effect. It also presents perhaps the best opportunity for policy improvement. Chicago already handles the distribution of rain barrels through the Rain Barrel Program, which makes the problem one of fine-tuning distribution. If the City can bring barrels closer to would-be adopters, significant gains in uptake can be achieved. Indeed, if all 863 tracts are brought within one mile of a distribution center, the marginal effects suggest that over 1,700 additional barrels would be adopted. Given that the City estimates 4,000 adoptions over the three years analyzed, this represents an increase of 43% in adoption.

Part V. More Barrels to More People: Optimization of Distribution Network

5.1 Motivation

The results of the econometric analysis of rain barrel adoption show potential gains to adoption from the reduction of average tract distance to a distribution location. After establishing the structure of incentives that affect adoption, the problem becomes one of optimization: how should policymakers select distribution locations for the Rain Barrel Program to achieve the highest possible adoption? While the site selection literature from operations research offers much insight to this problem, it is clear that the econometric results derived in previous sections are essential to the evaluation of any solutions. This creates complementarities between economics and numerical optimization, where the former provides a method to evaluate the solutions generated by the latter. The final part of the analysis will propose a framework that leverages these complementarities and presents a proof-of-concept.

5.2 Framework and Assumptions

Theoretically, there are many approaches the City could take to its rain barrel distribution problem. It could increase the number of available distribution locations; deliver barrels to residents' homes; or improve the selection of distribution points, to name a few. At one end of the solution spectrum, Chicago could minimize the cost to deliver rain barrels directly to residents, capitulating altogether on the current distribution framework. The solution is theoretically attractive and follows from the econometric result: if a reduction of average distance to one mile is good, then a reduction to zero miles is better. However, the cost of home delivery is likely to be much higher than setting up a few distribution points. The Rain Barrel Program may require additional vehicles to deliver the barrels; additional warehouse space to store the barrels before delivery; or additional personnel to manage the program. These costs would likely outweigh any gain from greater Program participation.

At the other end of the possible range of solutions, Chicago can try to improve adoption by making marginal changes to the way the Rain Barrel Program currently works. In particular, as motivated by the econometric results, the City's selection of distribution sites is likely to have a large effect upon adoption. By minimizing the distance between distribution sites and tracts, more barrels would be adopted. This course of action would be relatively inexpensive if no additional distribution sites are selected, apart from the additional subsidies and deliveries for the additional rain barrels. This will be the approach taken when formulating the rain barrel delivery problem and its constraints.

The conservation reserve selection and design literature provides a useful framework for addressing the problem of optimal distribution site selection. Williams et al. (2005) provides an overview of recent work on nature reserve design. The authors cover in detail the "species set covering problem" and its extensions, where an integer program selects the minimum number of sites to compose a reserve subject to a particular requirements for number of species, connectivity, shape, and other features. Among the formulations is a variant where reserve proximity enters explicitly into the minimization of the objective function, thereby promoting "connectivity" among parcels. Williams (2008) addresses this point more finely and presents two models (SDPAIR and SDCENT) where distance minimizations form the objectives. Dissanayake and Önal (2008) use a constrained distance minimization model that includes conditions for compactness, distance-related features, and considerations specific to certain species. This model provides perhaps the best match for the type of problem the City faces in rain barrel distribution. Slight modification can position the model to consider only distance between distribution and demand locations and minimize that as its objective.

While distance is a natural choice in conservation design, it may be a problem if budget considerations do not allow the policy prescribed by the solution. In the case of a logistical problem such as Chicago's, the incorporation of cost of distance traveled (and other costs) into the objective function may provide a better estimate of the total cost of implementing a particular distribution network. As such, distance-cost (distance times cost per distance unit traveled) will be used, as it is directly a function of distance, but can be weighed against any other costs involved.

Two major assumptions are made in order to make tractable the distribution site selection problem. The first assumption is that all distribution points are actually one-time events, and thus require a particular number of barrels ahead of time. This has implications for the structure of costs, as barrels can only be delivered by the literal truckload. The second assumption is that demand is taken as given. That is, the policymaker knows in advance where the buyers of rain barrels are located and chooses distribution locations after the fact. This is not how the Rain Barrel Program currently operates. Typically, either barrels are gathered in a location, advertised, and sold in one day events, or outdoor supply retailers sell the barrels all year. In neither case is demand known. However, it would be easy and relatively cheap for the City to gauge demand ahead of time and supply each event with just enough barrels. Without this assumption, one would be required to predict the quantity and location of demand, something which falls outside the scope of the data and methods applied.

5.3 Problem Statement and Model

Given the considerations outlined above, one may state the policymaker's problem as follows. Consider a central distribution location whose management wishes to choose "satellite" distribution sites to satisfy some known demand for rain barrels. Given a particular set of demand points, the managers would like to minimize the total cost of rain barrel delivery. Total cost is given by the sum of the distance-cost to each resident to pick up his or her barrel plus the total cost of supplying each site with enough barrels to satisfy demand. Satellite locations are supplied by the central location, but each delivery required to supply a satellite site is costly and provides only a fixed number of barrels. The managers wish to choose a limited number of satellites to fully satisfy demand at lowest cost.

Table 9 defines the variables used in the model. The model is mathematically formulated as follows:

$$\min \quad \sum_i \sum_j dc_{ij} x_{ij} + \sum_i tc_i N_i + \sum_i C_i y_i \qquad \text{Objective} \qquad (11)$$

s.t. $\sum_j x_{ij} \le Dn_i \quad \forall i$ Supply limit (12)

$\sum_i y_i \le M$ Number of distribution sites (13)

$\sum_i x_{ij} = 1 \quad \forall j$ Demand satisfaction (14)

The "objective" equation minimizes the sum of total distance-cost for both residents and the program manager, who has to ship barrels from the central to the satellite locations. The last term in the equation, which is added to complete the model, is the fixed cost of renting the site. The "supply limit" constraint ensures that the chosen distribution locations do not supply more barrels than they have received from the central distributor. "Number of distribution sites" constrains the model to choose at most *M* satellites, and "demand satisfaction" forces the model to supply all given demand points.

5.4 Application: 2004 Rain Barrel Delivery

The simple model described above captures the salient features of Chicago's rain barrel distribution problem. To test the model, adoption data from year 2004 of Chicago's Rain Barrel program are used. The data contain 397 addresses and 6 distribution event locations. In addition to these 6 points, 25 additional possible distribution sites were arbitrarily chosen. The points were chosen to substantially cover the landscape while avoiding major geographical features that might make them poor choices (specifically, points are not in bodies of water or airports). The number of possible sites is kept small to allow the model to be solved quickly.

Parameters for the model were chosen to reflect realistic costs. To measure cost of distance traveled to residents, the IRS business mileage rate of \$0.585 per mile for the second half of 2008 was used.[6] Distance-cost for truck freight is \$1.90 per mile and was obtained online from the U.S. Freight Rate Index.[7] Because Chicago is laid out in blocks, distance is measured as the sum of east-west plus north-south distance traveled between the delivery location and distribution point. Given the standard dimensions of both 55

[6] http://www.irs.gov/newsroom/article/0,,id=200505,00.html

[7] Obtained December 2008 from http://wwwhst.com/freightrateindex/. The index reflects all operating costs for trucking in the United States.

gallon rain barrels and semi truck trailers, about 225 barrels can be accommodated per shipment.[8] This was the number used for maximum number of barrels per delivery. In the absence of information regarding the costs for securing distribution sites, it is assumed that these costs are zero. Because of this, the model essentially reduces to a weighted distance minimization.

The methodology employed here is intended to be conservative. As such, only explicit costs are included as part of the site selection process. There is no measure of opportunity cost to residents in terms of leisure or work time foregone to pick up the barrels or find out about nearby distribution events. These additional costs guarantee that any actual objective inefficiency—as reflected in the difference between the optimal solution and the actual 2004 setup—is understated in this model.

Figure 18 illustrates the solution for the optimization when the model is constrained to the six actual 2004 distribution locations. The solution reflects a best-case assumption where each demand point is supplied by the distribution location closest to it. The delivery points are colored and shaped such that they match their optimal distribution locations given by the bigger points. The objective value for this solution is $1,418.62 with delivery points at an average distance of 2.09 miles from the nearest distribution location.

Figure 19 illustrates the solution to the optimization when the model is allowed to choose among the 31 possible distribution locations. Again, the delivery points are colored and shaped such that they match their optimal distribution locations given by the bigger points. The objective value for this solution is $1,238.93 with delivery points at an average distance of 1.76 miles from the nearest distribution location. The solution reflects an optimum for the specific parameterization of the model and is sensitive to those values.

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[8] A semi truck trailer is typically 8.5 feet wide, 53 feet long, and 13.6 feet tall. A 55 gallon barrel has diameter of about 23 inches and height of 34 inches.

A comparison between the models shows that the optimal solution improves on the best-case 2004 objective outcome by 12.7%. Distance is reduced by 15.8% to 1.76 miles. To evaluate the implications for adoption, the analysis uses the marginal effect of the reduction in distance using the econometric results derived in earlier sections. A reduction of 0.33 miles in tract distance from distribution point produces an increase in adoption of 0.22 barrels per tract, all else equal. Given that 68 tracts purchased at least one barrel in 2004, this represents an increase of about 16 additional barrels, or about 4%. This modest increase in adoption can be taken as a lower bound, as it rules out the possibility that residents in other tracts will choose to purchase rain barrels once they are brought closer. A similar marginal analysis using the logit shows an increase in odds of adoption of about 1%, from 69% to 70%.

Part VI. Conclusions

This analysis of rain barrel adoption patterns contributes to several areas of economic research. It adds to the technology diffusion literature by studying the factors that underlie the deployment and growth of a new rainwater harvesting technology. Green technology adoption may be affected by education campaigns, socioeconomic factors, environmental ideology, and transaction costs, all of which are investigated here. This research explores whether owner-occupancy significantly reduces agency problems and whether certain aspects of housing type affect adoption. It analyzes whether consumer behavior can be affected by environmental outcomes like basement flooding. Lastly, it also investigates spatial correlation in adoption patterns, which could be associated with the diffusion of knowledge related to a new technology. Separately, this study applies the results of the econometric analysis in an optimization exercise to generate an estimate of the possible gains in adoption from improved rain barrel distribution.

The findings of this study may help Chicago better direct its Water Agenda and stormwater management policies. Rain barrels are shown to be a normal good, with higher numbers found in higher-income areas. There is a strong positive correlation between "green" political ideology and rain barrel adoption, which supports the findings in Kahn (2007). A desire for particular geographical dispersions of barrels across city may call for targeted advertisement outside these areas. The City could also choose to deploy in those areas stormwater management technologies that do not require resident participation.

Green Alleys likely have a positive effect on rain barrel adoption, which may imply that educational programs encourage uptake of a green technology even without subsidies. More work would be needed to identify whether the Green Alleys themselves are an important part of this program or whether the effect of education dominates. There is no evidence that more rain barrels are purchased in parts of the City with greater incidences of reported basement flooding, and two conclusions are possible here. On one hand, the City may not be adequately connecting the ideas of local stormwater management and rain barrel use, although barrels have been advertised in this way. Perhaps additional education would help. On the other, it may be that rain barrels do not provide adequate basement flood deterrence, and consequently residents are springing for solutions other than rain barrels.

This work sheds light on several dimensions of transaction costs related to rain barrel adoption. While the proportion of single-unit structures is not important, higher fractions of multi-family structures with ten units or more implies fewer adoptions. This is consistent with the difficulty of accommodating a rain barrel in an apartment setting and the limited safe indoor rainwater uses. In parts of the city dominated by large apartment buildings and commercial structures, decentralized stormwater control might need to be focused more on green roofs, rain gardens, and other LID practices. The experiences of Australia and Europe indicate that large cisterns may have a role to play when outfitting multifamily structures for stormwater management, with trickle-fed tanks providing an attractive complement to municipal water supply.

Distance from a distribution point is an important determinant of adoption and provides the Department of Environment with one possible metric to target as it attempts to grow adoption. The model presented in the Part V provides an informative combination of econometrics and numerical optimization that fills the gap between the identification of policy controlled variables and the improved policy itself. The optimization model and its implementation comprise a framework for achieving some of the gains identified using econometrics.

The optimization model is not free of shortcomings. First, like many models of this kind, the choice of parameters plays an important part in determining the solutions. Second, the objective values are useful only for comparisons between solutions. Although the solution is dollar denominated, it is unlikely to reflect the actual cost of the policy. Third, the thrust of the model is to improve adoption by bringing barrels closer to customers while acknowledging additional costs and major constraints. If a majority of costs is not recognized—which they may not be, as the Rain Barrel Program's costs are reflected throughout the Department of Environment's finances—the results are questionable.

The analysis has tried to address these potential shortcomings by adopting conservative estimates and parameters. In deriving potential gains from redistricting distribution, the model assumes the optimum outcomes for actual 2004 distribution. It assumes no rent for distribution sites, where an optimum policy would likely call for fewer than 6 sites if rents are positive. The cost of trucking assumes only per-mile cost to ship very short distances from the central distribution location and no cost to residents other than vehicle operation. Finally, the estimate of minimum gains assumes additional barrels will be purchased only in tracts with previous adoption, and that no additional adoptions will result from residents' ability to order barrels in advance (although costs for the latter are not recognized).

Regardless of these assumptions, there are gains to be had from an improved distribution network. By taking orders before distribution, the City is able to better plan its logistics to minimize total costs of adoption for its residents. This may be costly, but it is likely to be relatively cheap if done through the mail or using electronic communication. If rain barrels do indeed provide an environmental benefit that exceeds that cost of the subsidy, improved adoption will both reduce the social costs (experienced by the Rain Barrel Program and residents) and increase the social benefits through improved stormwater management.

Tables and Figures

Table 1: Rain Barrel Adoption, Costs, and Available Addresses

Year	Est. Barrels Distributed	Cost to City (per barrel)	Cost to residents (per barrel)	Addresses available
2004	500	$70	$15	397
2006	1400	$78	$20	1000 [a]
2007	1950	$78	$40	1376 [b]

[a] This number was changed from 1001 to 1000 to reflect dropped observations.
[b] This number was changed from 1377 to 1376 to reflect dropped observations.

Table 2: Variable Descriptions

Variable	Type	Description
Total rain barrels	Dependent	Total rain barrels purchased in years 2004, 2006, and 2007, from Chicago Department of Environment officials
Dummy, tract has at least one barrel	Dependent	Dummy, tract has at least one barrel purchased in years 2004, 2006 and 2007
Median age	Independent	Median population age, from Census Summary File 1
Housing units occupied	Independent	Housing units occupied, from Census Summary File 3
Housing units owner-occupied	Independent	Housing units occupied by owner, from Census Summary File 3
% votes Republican	Independent	Proportion of population that voted Republican in 2006 gubernatorial election
% votes Green	Independent	Proportion of population that voted Green in 2006 gubernatorial election
Median HH income	Independent	Median household income ($10,000), from Census Summary File 3
% single-unit building	Independent	Proportion of housing stock that a single attached or detached residential unit in the structure, from Census Summary File 3
% 10+ unit building	Independent	Proportion of housing stock has 10+ residential units in the structure, from Census Summary File 3
% with at least bachelor's degree	Independent	Proportion of pop. 25 years or older with at least a bachelor's degree, from Census Summary File 3
% do not own a car	Independent	Proportion of occupied households who do not own a car, from Census Summary File 3
# of basement floods	Independent	Average number of basement floods, from Chicago Department of Environment officials; average count of water-in-basement occurrences in years 2003, 2005, and 2006
Distance to distribution center	Independent	Average dist. to nearest distribution center (1,000 m); distance computed as a straight line to the nearest distribution point available each year, and average is the mean over the study's years; distribution points obtained from Chicago Department of Environment officials
Tract has a Green Alley	Independent	Tract has a Green Alley, obtained from Chicago Department of Environment officials; Green Alleys were coded into ArcMap and value of 1 is assigned to any tract that intersects an Alley

Table 3: Summary Statistics

Variable	Mean	Std. Dev.	Min	Max
Total rain barrels	3.21	5.44	0	48
Dummy, tract has at least one barrel	0.630	0.483	0	1
Median population age	31.49	5.97	14.2	64.1
Housing units occupied (1,000)	1.25	1.06	0.001	6.95
Housing units occupied by owner (1,000)	0.55	0.56	0	3.40
% of owner-occupied units	42.23	23.26	0	100
% pop. voted Republican	13.25	11.72	0	49.49
% pop. voted Green	6.99	5.56	0	23.82
Median household income ($10,000)	3.79	1.84	0.25	20.00
% total housing stock: single-unit building	29.69	26.24	0	100
% total housing stock: 10+ unit building	21.70	26.79	0	100
% pop. with at least a bachelor's degree	23.13	22.63	0	100
% households who do not own a car	30.29	17.50	0	100
Average number of basement floods	7.71	10.80	0	129
Average dist. to nearest distribution center (1,000 m)	6.49	3.20	0.30	16.24
Tract has a Green Alley	0.044	0.21	0	1

Table 4: Results for Non-spatial Regressions[a]

	Logit	Neg. bin.	Logit	Neg. bin.
Ward dummies			Significant[b]	Significant[c]
Median age	0.016 (0.019)	0.024*** (0.008)	0.0002 (0.0231)	0.013 (0.010)
Housing units occupied	0.987*** (0.248)	0.372*** (0.051)	0.885*** (0.269)	0.256*** (0.057)
Housing units owner-occupied	-0.051 (0.534)	0.176 (0.114)	0.335 (0.590)	0.452*** (0.124)
% votes Republican	-0.021 (0.015)	0.005 (0.005)	0.011 (0.025)	-0.008 (0.006)
% votes Green	0.224*** (0.036)	0.140*** (0.009)	0.176*** (0.048)	0.127*** (0.012)
Median HH income	0.582*** (0.211)	0.315*** (0.115)	0.613*** (0.233)	0.313*** (0.121)
(Median HH income)^2	-0.019 (0.014)	-0.018** (0.009)	-0.017 (0.014)	-0.015* (0.009)
% single-unit building	0.009 (0.006)	0.007*** (0.002)	0.006 (0.007)	0.001 (0.002)
% 10+ unit building	-0.016*** (0.006)	-0.012*** (0.002)	-0.015** (0.007)	-0.014*** (0.003)
% with at least bachelor's degree	-0.018** (0.009)	-0.015*** (0.003)	-0.017 (0.011)	-0.001 (0.004)
% do not own a car	0.010 (0.01)	-0.004 (0.005)	0.021* (0.011)	0.007 (0.005)
# of basement floods	0.003 (0.014)	0.002 (0.003)	-0.011 (0.018)	-0.002 (0.004)
Distance to distribution center	-0.112*** (0.029)	-0.106*** (0.014)	-0.127 (0.090)	-0.128*** (0.032)
Tract has a Green Alley	0.060 (0.453)	0.159 (0.126)	0.431 (0.490)	0.320*** (0.121)
Constant	-3.083*** (0.909)	-1.559*** (0.435)	([d])	-1.102** (0.533)
Log likelihood	-390.38	-1553.66	-347.84	-1474.46

[a] Standard errors in parentheses. * 10% significance; ** 5% significance; *** 1% significance. [b] $\chi^2 = 339.98$; $\Pr(F \le \chi^2) < 0.001$ [c] $\chi^2 = 179.8$; $\Pr(F \le \chi^2) < 0.001$

[d] The standard error for the constant is ill-defined in this regression because the coefficients on some of the ward dummies are perfectly determined.

Table 5: Results for Spatial Regressions[a]

	SEM Logit	SAR Logit
λ (Spat. err. coeff.)	0.010 (0.013)	-
ρ (spatial autocorr. coeff.)	-	0.011 (0.011)
Median age	0.005 (0.013)	0.006 (0.015)
Housing units occupied	0.520*** (0.142)	0.579*** (0.177)
Housing units owner-occupied	-0.007 (0.312)	-0.024 (0.38)
% voted Republican	-0.009 (0.010)	-0.010 (0.011)
% voted Green	0.129*** (0.022)	0.136*** (0.026)
Median HH income	0.408*** (0.146)	0.469*** (0.176)
(Median HH income)^2	-0.016** (0.010)	-0.018** (0.012)
% single-unit building	0.006* (0.004)	0.005 (0.004)
% 10+ unit building	-0.009*** (0.004)	-0.010*** (0.004)
% with at least a bachelor's degree	-0.011** (0.006)	-0.012** (0.007)
% do not own a car	0.005 (0.006)	0.006 (0.008)
Average # of basement floods	0.005 (0.009)	0.007 (0.011)
Avg. distance to distribution center	-0.069*** (0.020)	-0.070*** (0.023)
Tract has Green Alley	0.081 (0.290)	0.140 (0.346)
Constant	-1.799*** (0.614)	-2.094*** (0.720)

[a] Standard errors in parentheses. * 10% significance; ** 5% significance; *** 1% significance.

Table 6: Marginal Effects

Variable	Logit Model Effect (ΔPr(Y) / ΔX)	Negative Binomial Model Effect (ΔY / ΔX)
Median age	0.0033	0.0386
Housing units occupied	0.205	0.6027
Housing units owner-occupied	-0.0106	0.2846
% voted Republican	-0.0043	0.0079
% voted Green	0.0465	0.2273
Median HH income	0.1209	0.5111
(Median HH income)^2	-0.0039	-0.0299
% living in stand-alone building	0.0019	0.0109
% living in 10+ unit building	-0.0034	-0.0192
% with at least a bachelor's degree	-0.0037	-0.0236
% do not own a car	0.002	-0.0066
Average # of basement floods	0.0007	0.003
Avg. distance to distribution center	-0.0233	-0.1711
Tract has a Green Alley	0.0124	0.2768

Table 7: Thought Experiments

Variable	Base Value	New Value	ΔPr(*Y*) Logit	Δ*Y* Neg. Bin.
Housing stock: 10% shift from single to 10+ [(a)]	10+ = 9.6% Single = 20.2%	10+ = 19.6% Single = 10.2%	-3.9%	-0.59
% votes Green [(c)]	0%	23.8%	61.0%	25.09
Income [(a)]	$37,000	$47,000	6.9%	0.51
Dist. from distrib. site [(b)]	4.1 miles	1 mile	8.0%	1.97
Dist. from distrib. site [(b)]	4.1 miles	0 miles	10.5%	2.87
Green Alley? [(c)]	no	yes	-	0.55

Note: These effects are calculated as follows. A prediction is generated for each observation with the variable of interest set equal to the base value, and then another prediction is generated for each observation with the variable of interest set equal to the new value. Other variables are held at their true values in the data. The difference between the means of those predictions is reported.

[(a)] Base value is the variable median.
[(b)] Base value is the variable mean.
[(c)] Base value is the variable minimum.

Table 8: Predicted versus Observed Outcomes for Logit Analysis

Predicted	Observed: No barrels	Observed: 1+ barrels	Observed: Total
No barrels	213	81	294
1+ barrels	106	463	569
Total	319	544	863

Note: This table uses the regression results from column 1 of Table 2. The predicted outcome is "1+ barrels" if the predicted probability is greater than .5 and "No barrels" otherwise.

Table 9: Variable Definitions for Optimization Model

Variable	Definition
i	distribution point candidate
j	final destination or delivery point
dc_{ij}	distance cost between delivery point j and distribution point i
tc_i	distance cost of delivery to distribution point i
C_i	fixed cost of choosing distribution point i
x_{ij}	1 if i supplies j; zero otherwise
y_i	1 if i is chosen as a distribution point; zero otherwise
n_i	number of trips to distribution point i
M	number of distribution sites
D	maximum number of barrels per delivery

Figure 1: Map of Chicago Census Tract and City Wards

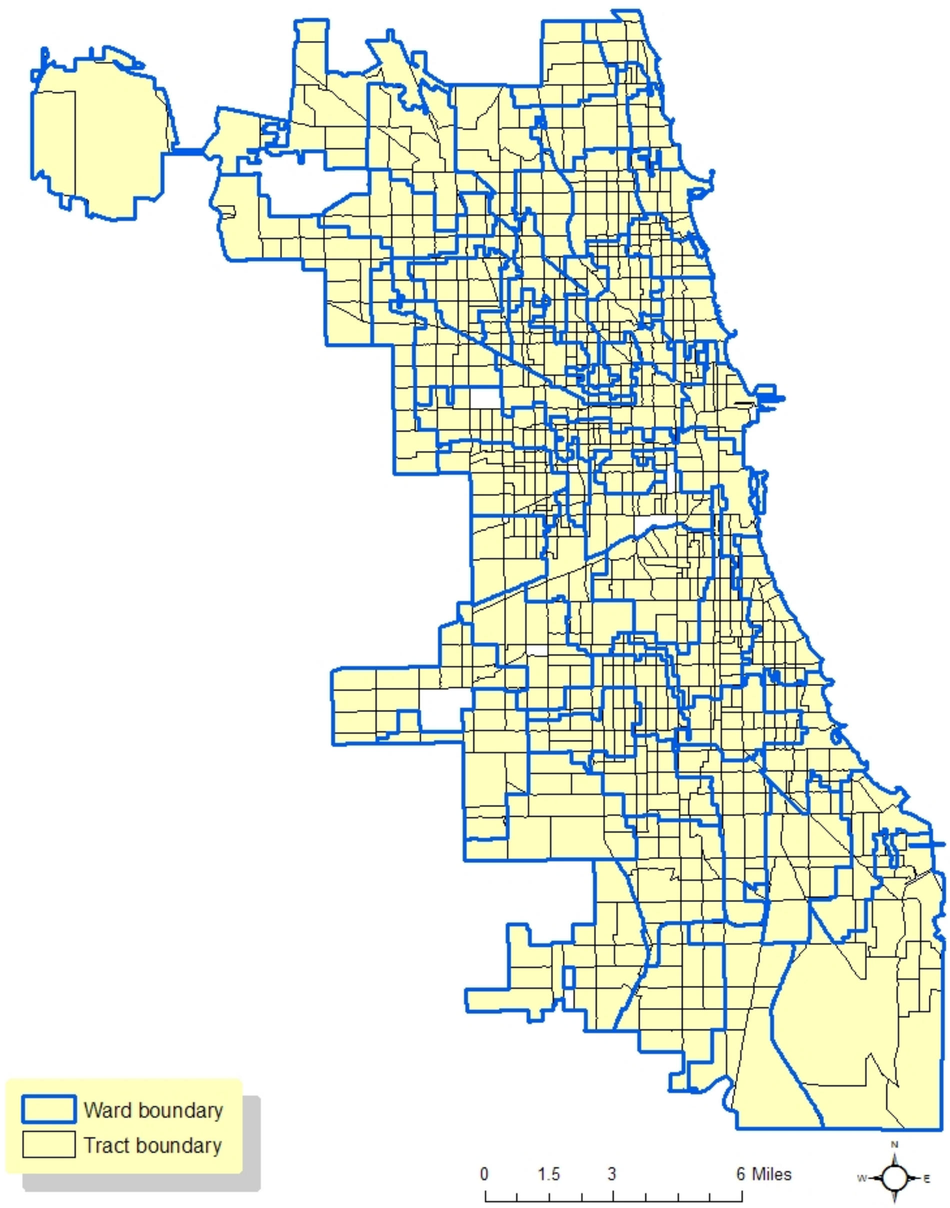
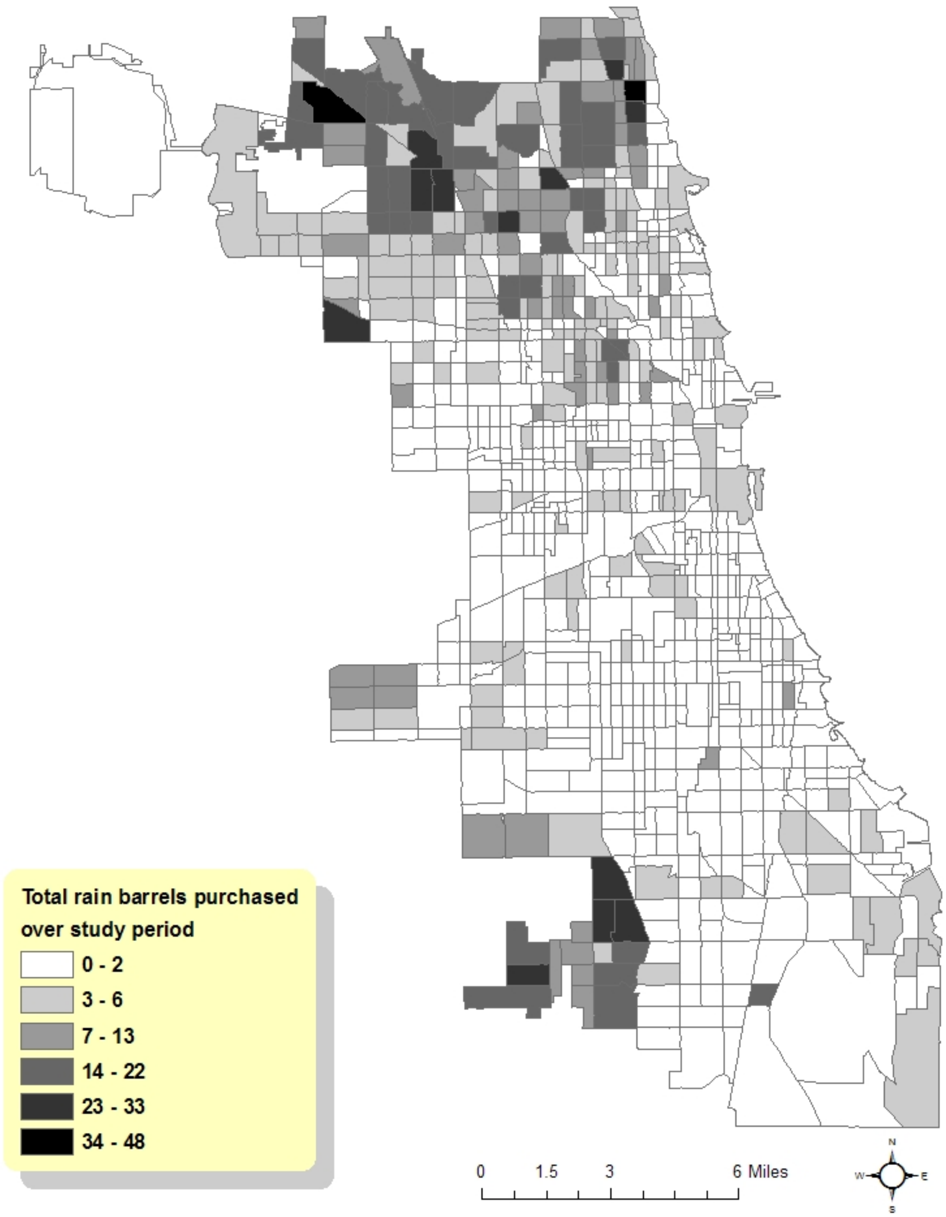
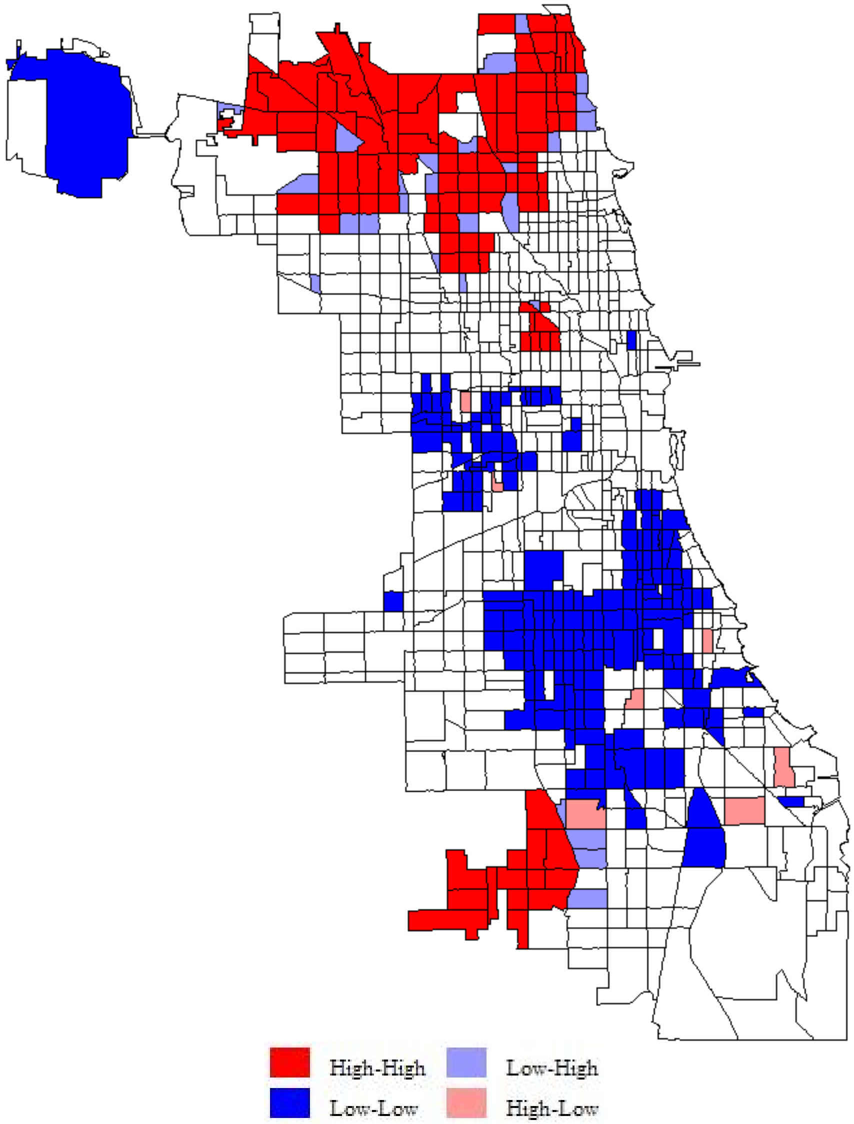


Figure 2: Map of Rain Barrel Adoption, by Tract



N=2775

Figure 3: Map of Local Spatial Autocorrelation, by Tract



Note: This is a queen-weighted LISA Cluster Map carried out using GeoDa (https://www.geoda.uiuc.edu/).

Figure 4: Map of Republican Voting (Percent), by Tract

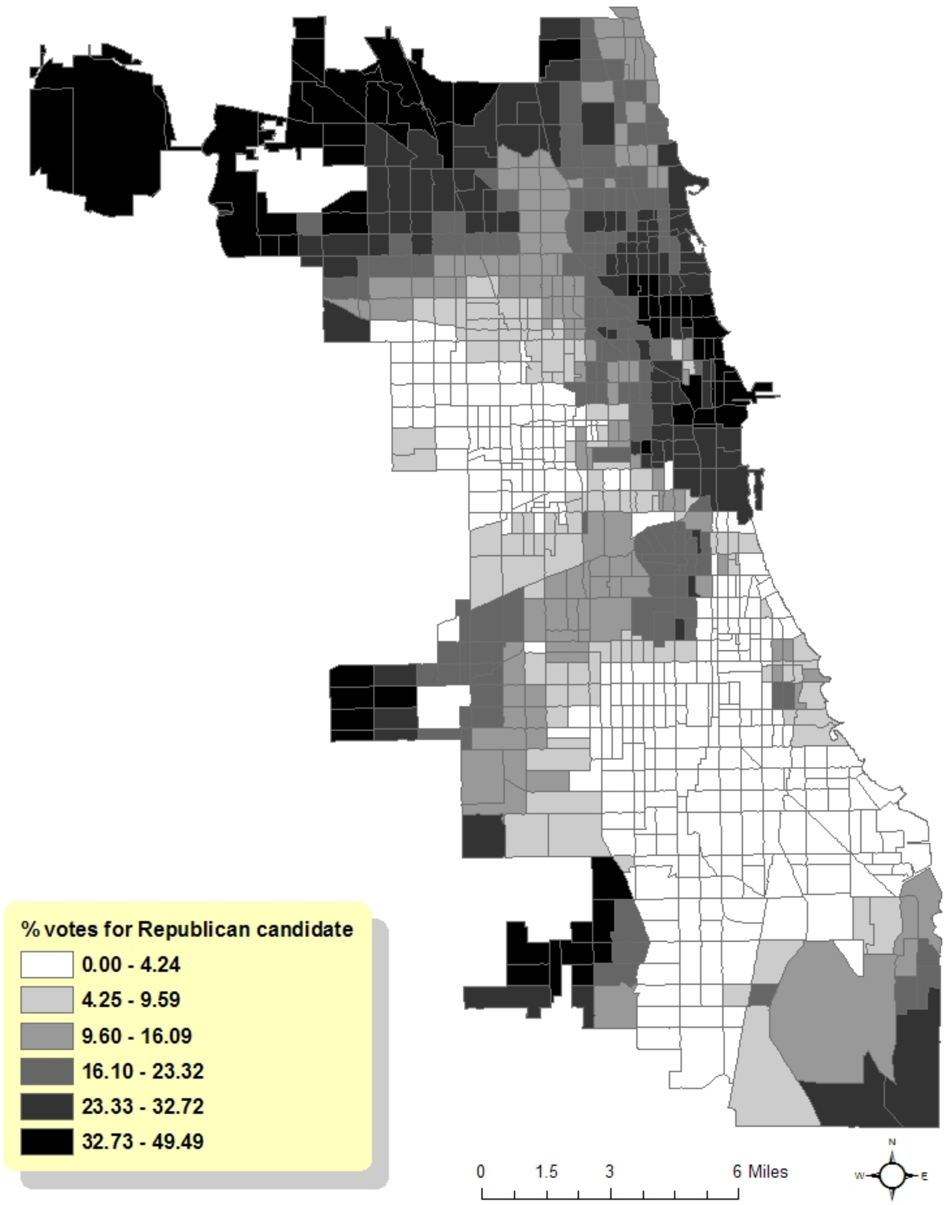


Figure 5: Map of Green Voting (Percent), by Tract

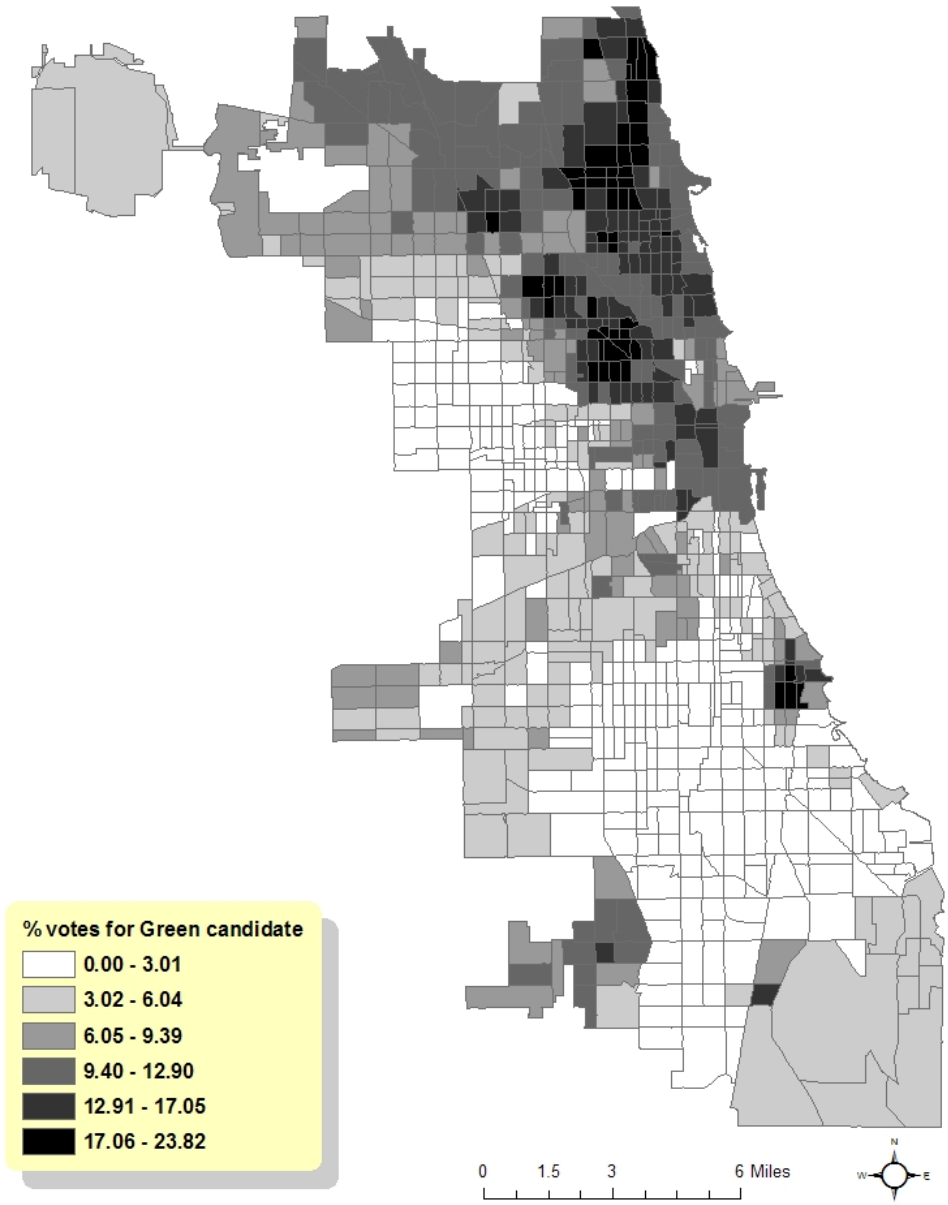


Figure 6: Map of Basement Flooding, by Tract

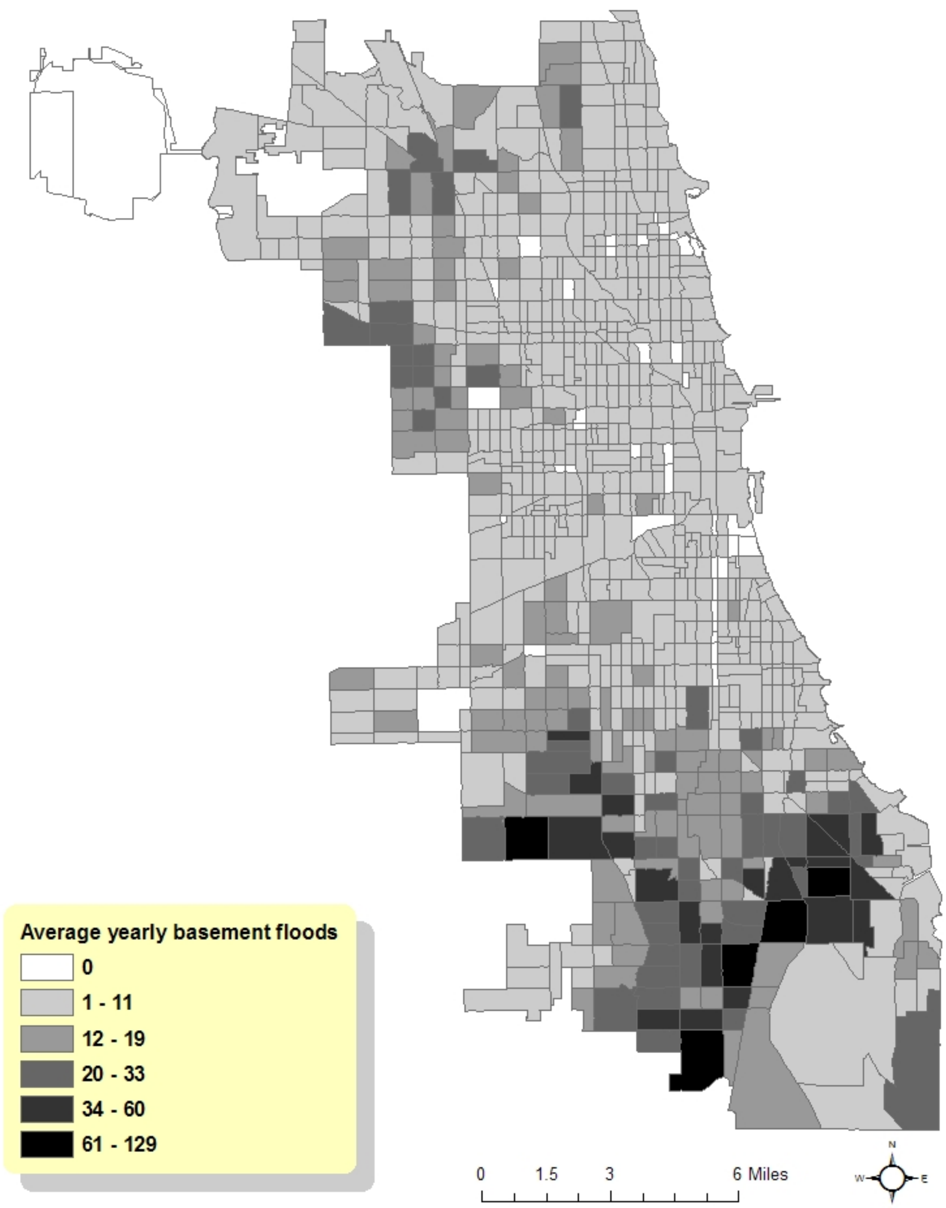


Figure 7: Map of Owner Occupied Households without Access to a Personal Vehicle (Percent), by Tract

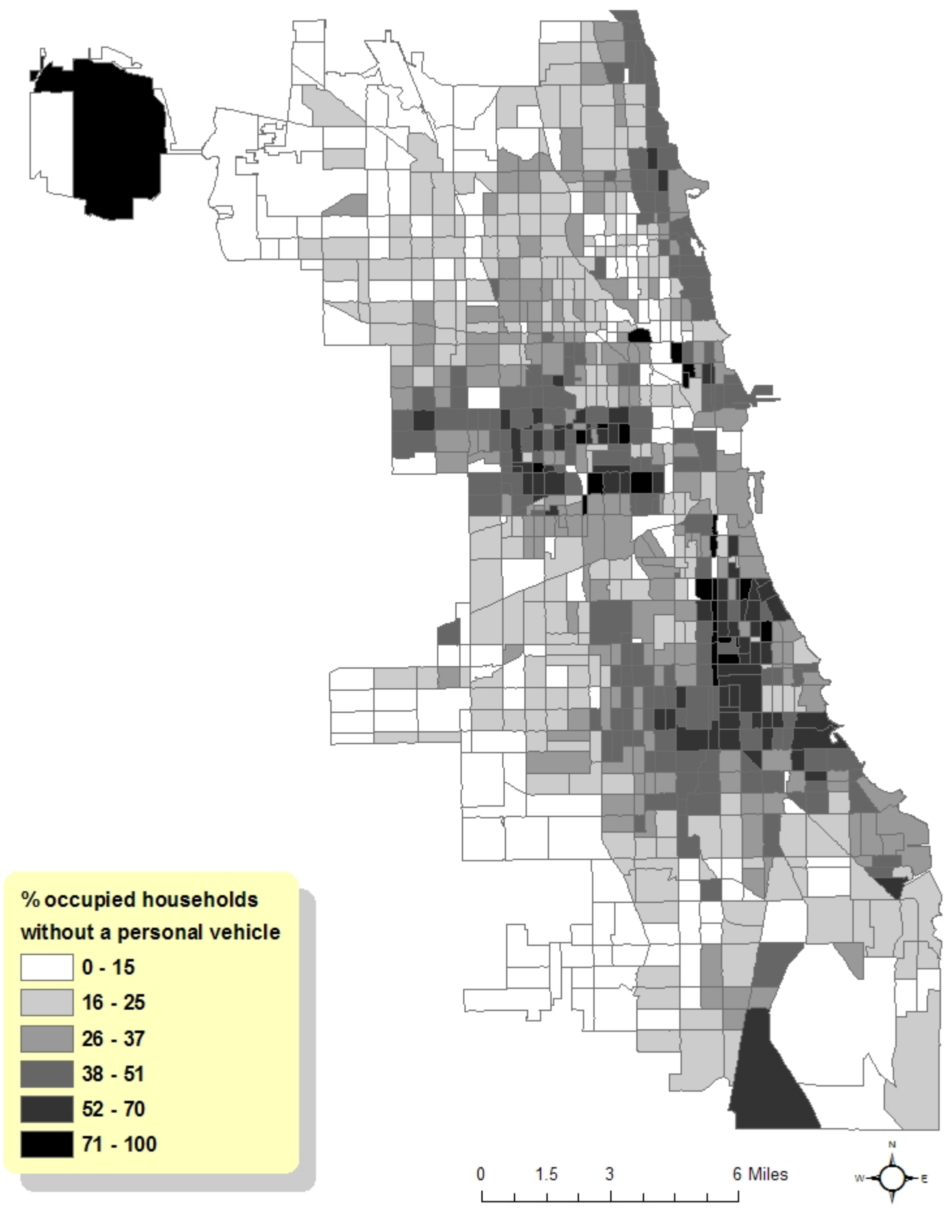


Figure 8: Map of Median Population Age (Years), by Tract

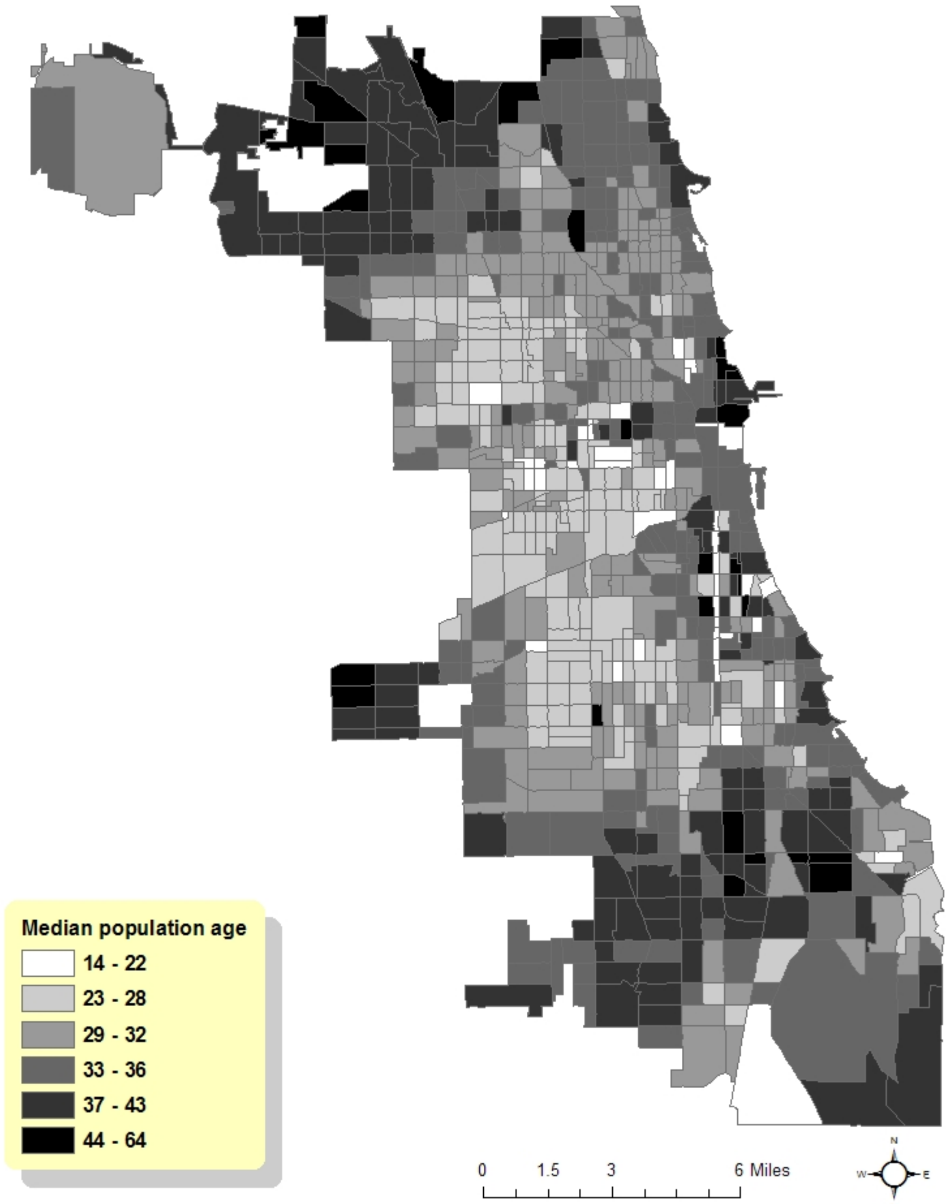


Figure 9: Map of Median Household Income in ($10,000), by Tract

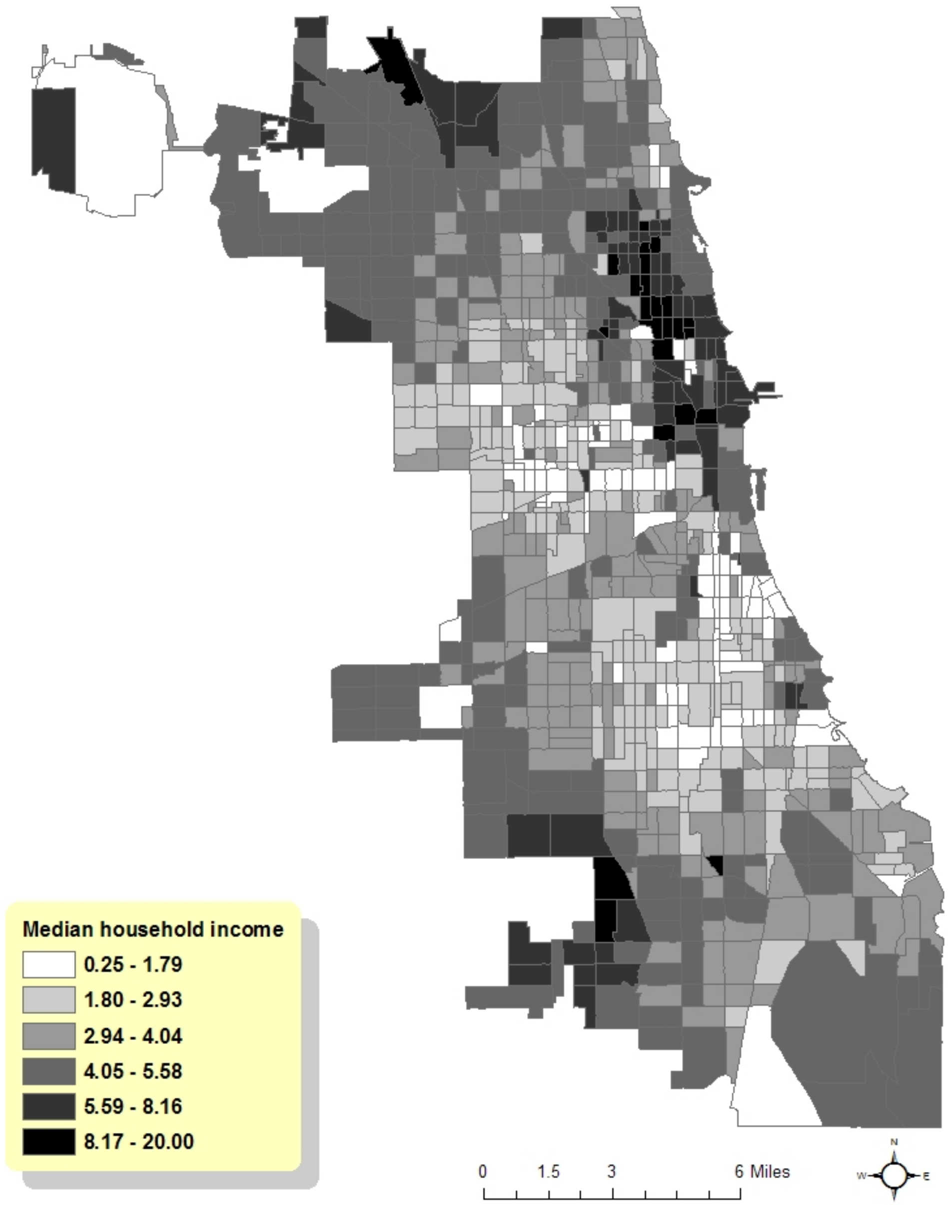


Figure 10: Map of Number of Occupied Housing Units (Thousands), by Tract

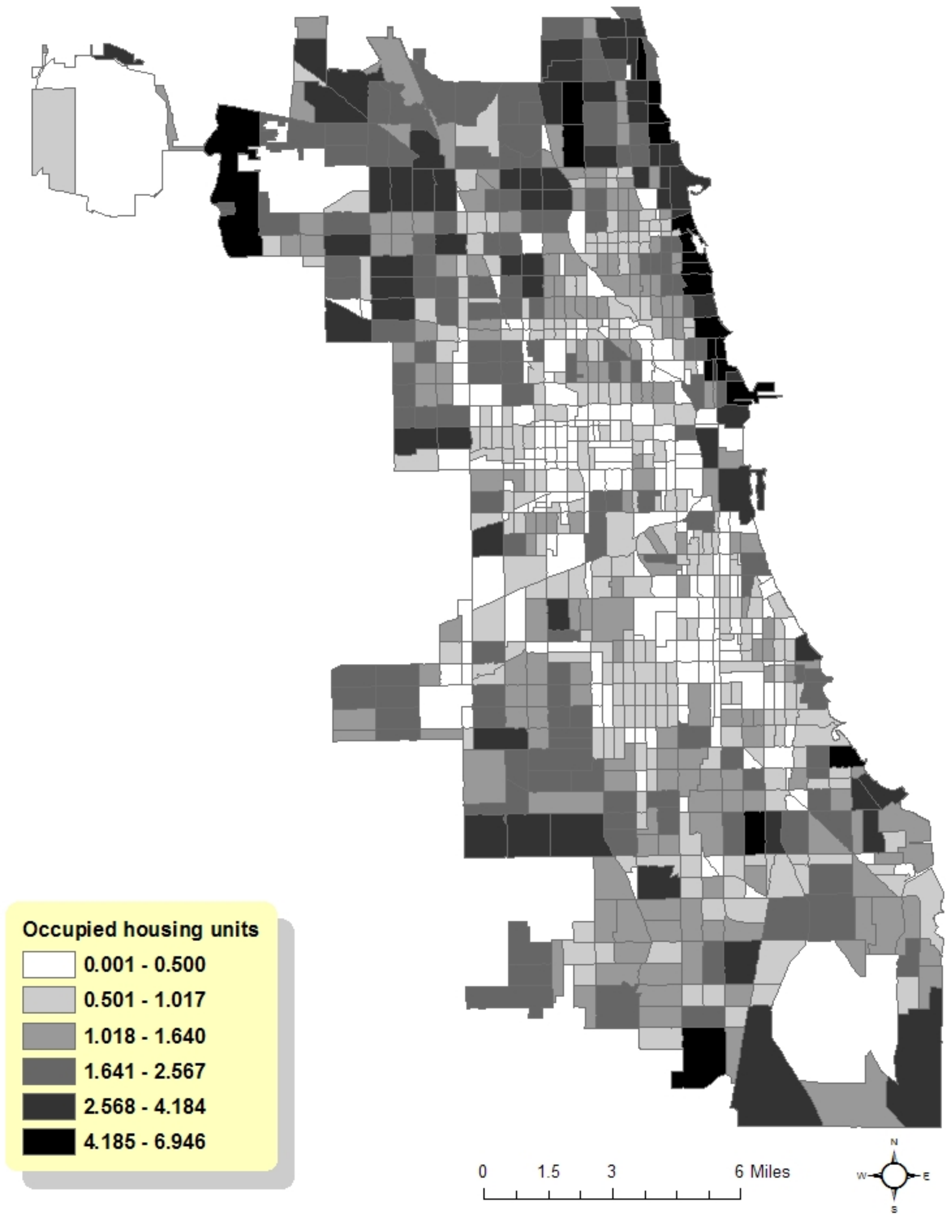


Figure 11: Map of Housing Stock in 10+ Unit Structures (Percent), by Tract

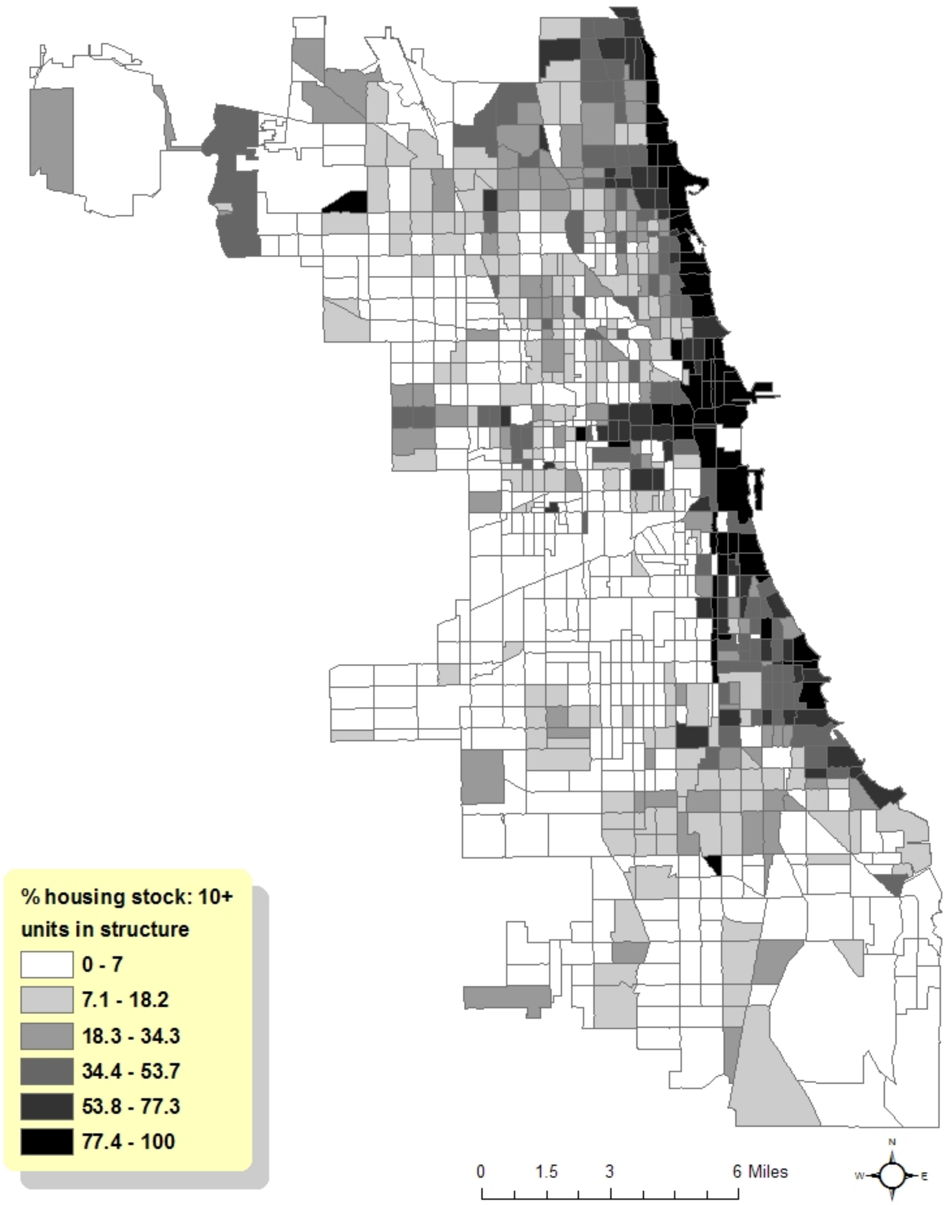


Figure 12: Map of Housing Stock in Single Unit Attached or Detached Structures (Percent), by Tract

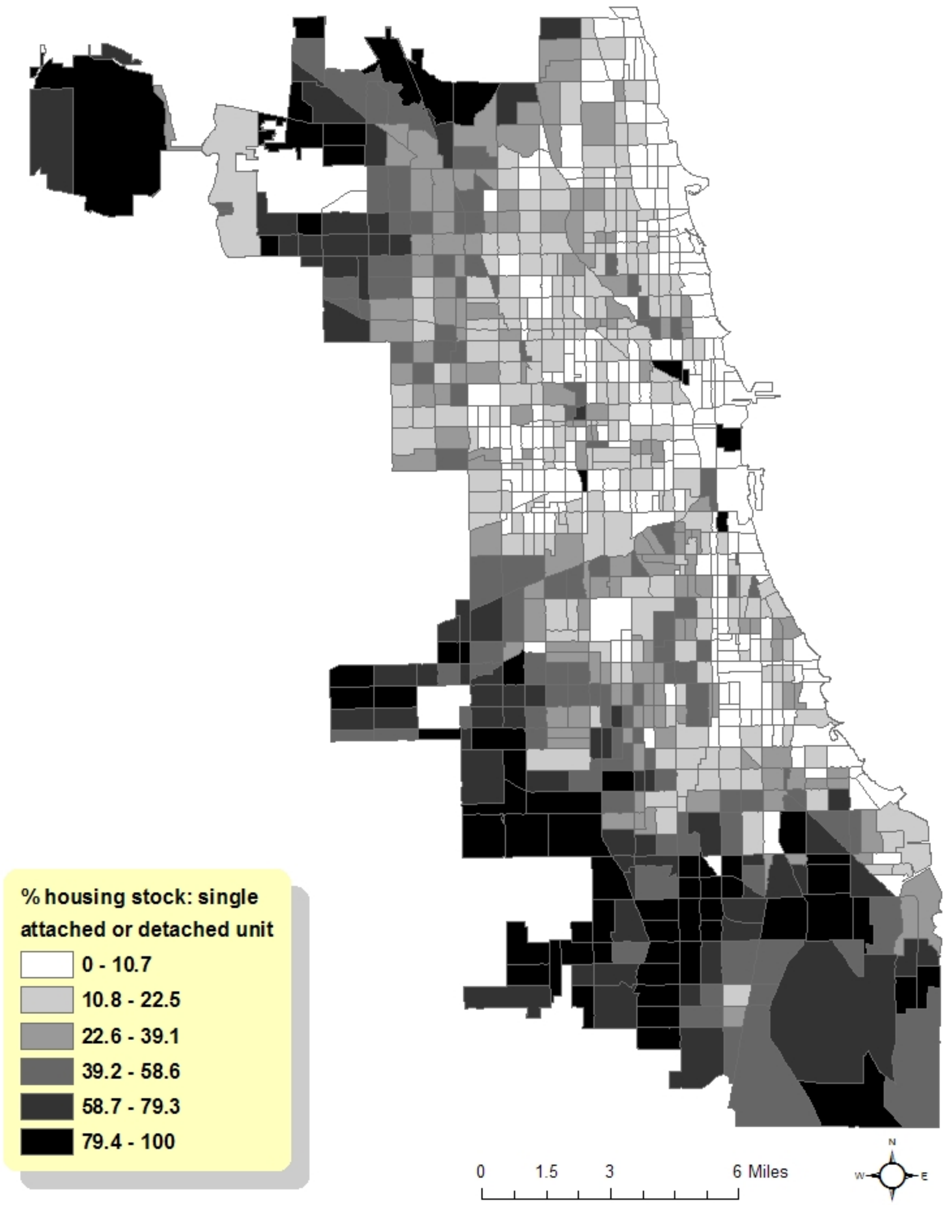


Figure 13: Map of Owner Occupancy, by Tract

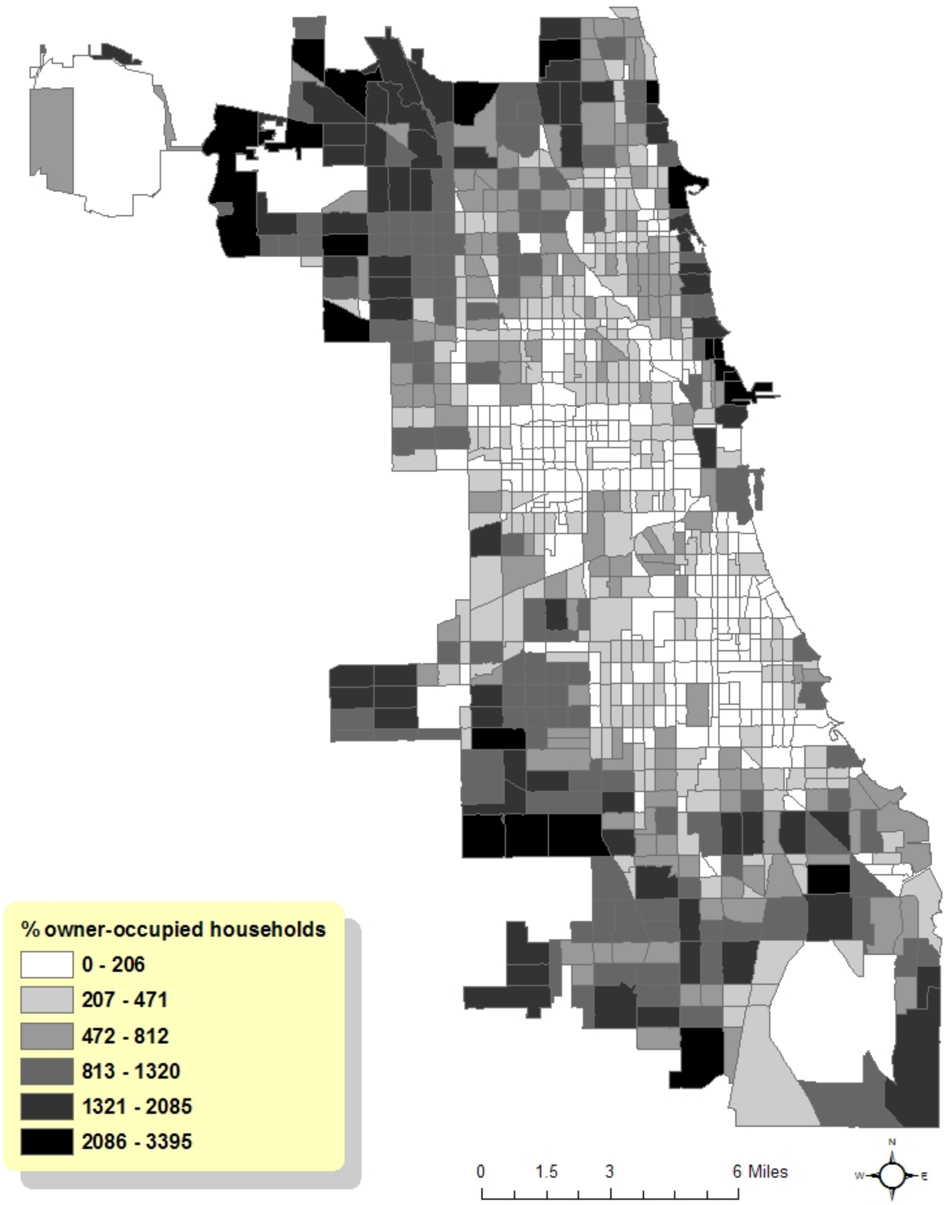


Figure 14: Map of Average Distance to Nearest Distribution Location (1,000 m), by Tract

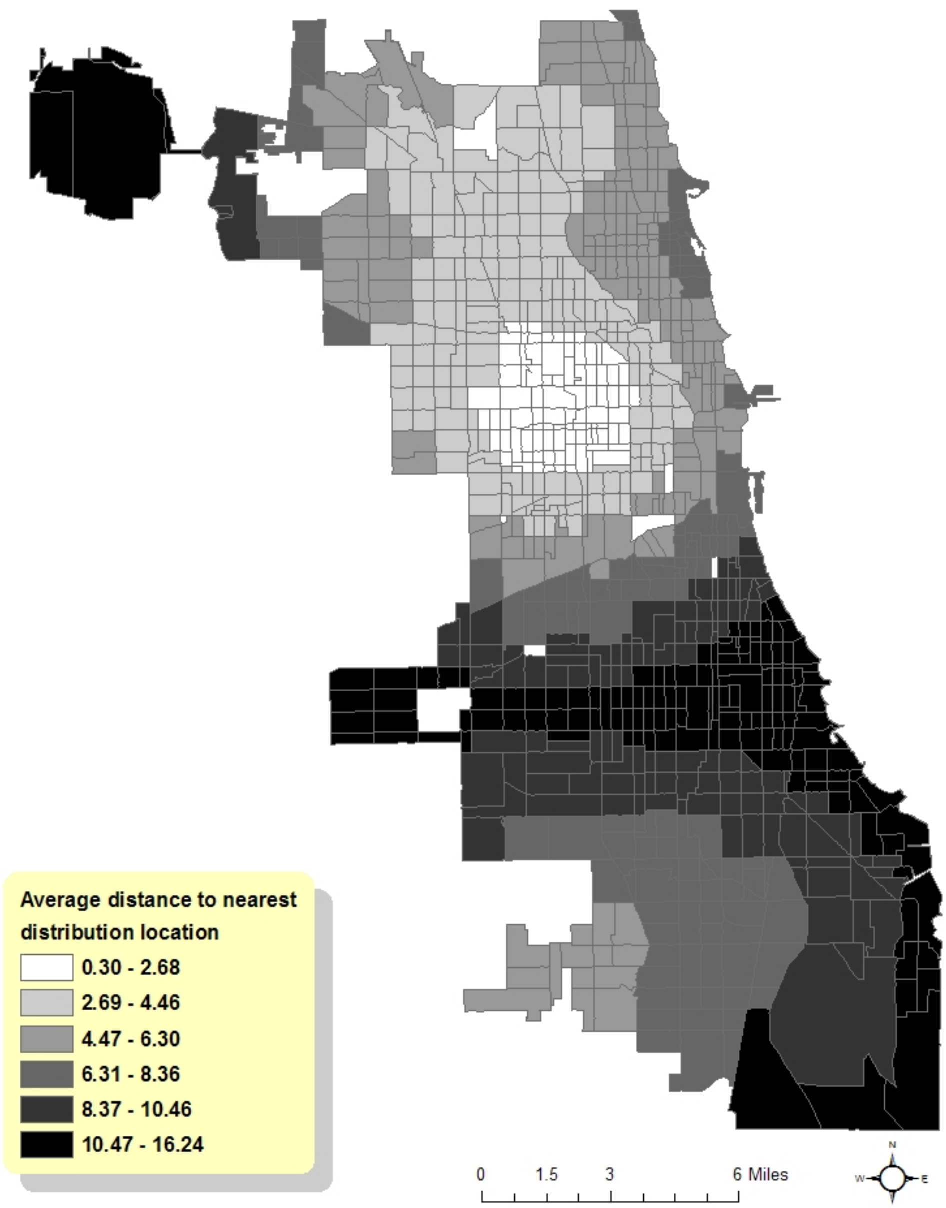


Figure 15: Map of Green Alleys Intersections, by Tract

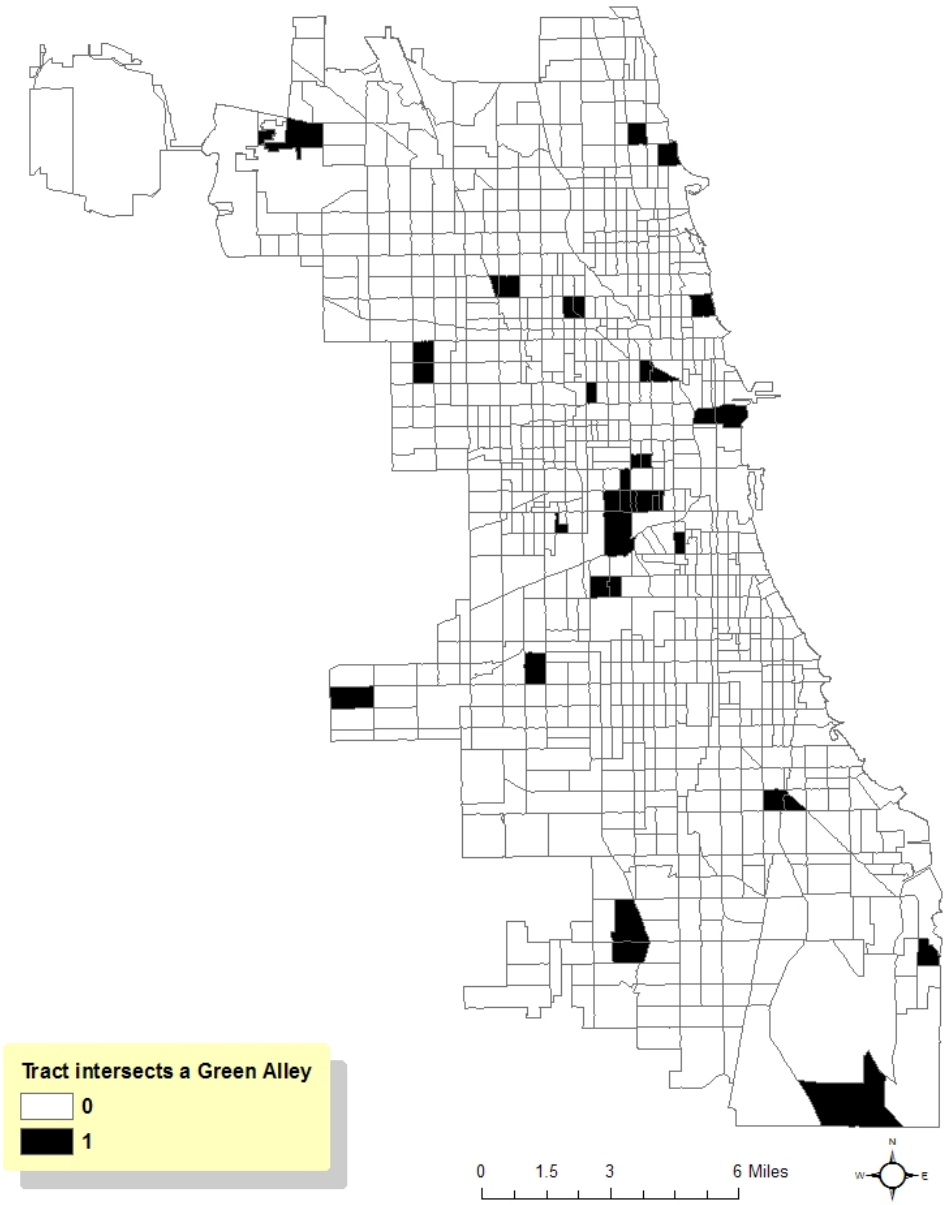


Figure 16: Map of Population 25 Years or Older with at Least a Bachelor's Degree (Percent), by Tract

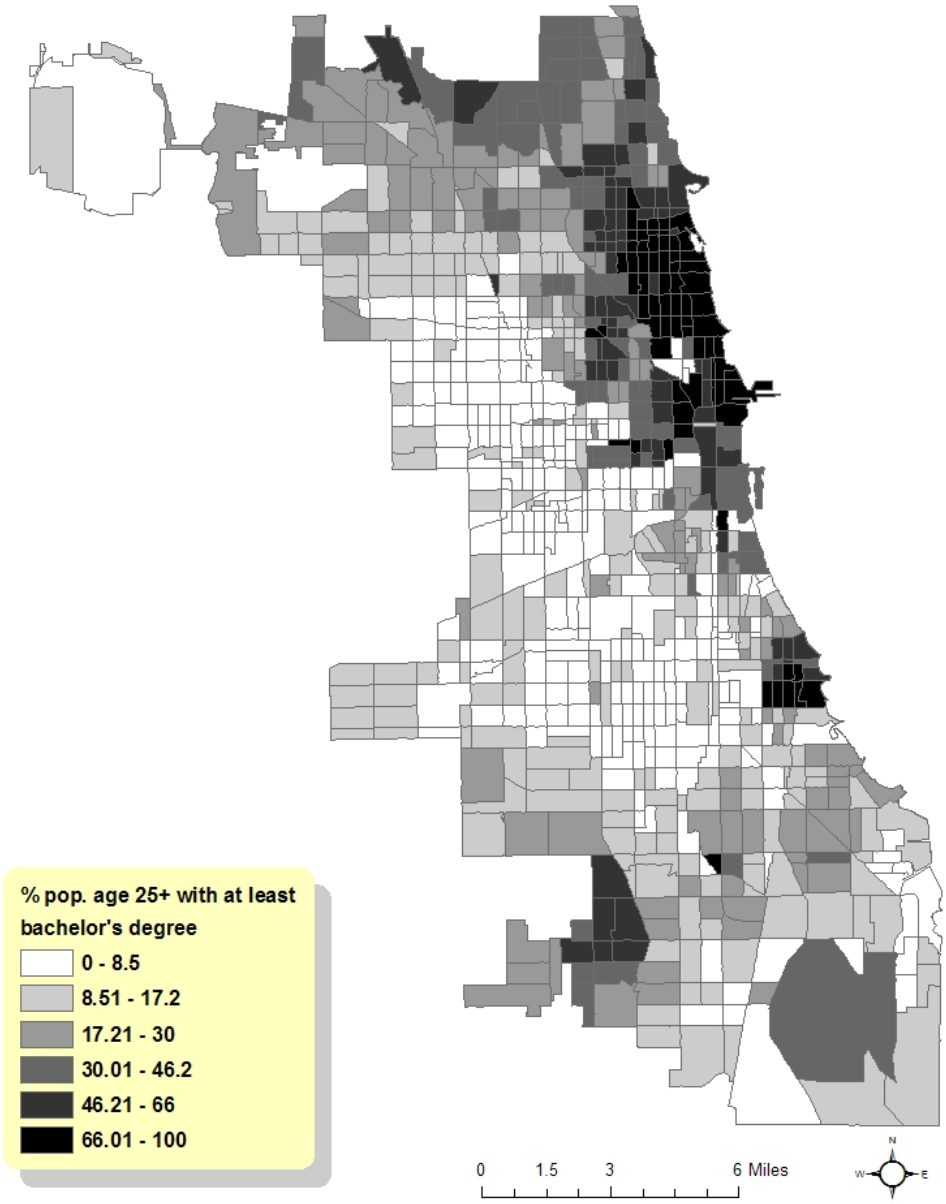


Figure 17: **Actual versus Predicted Number of Barrels from Negative Binomial Regression**

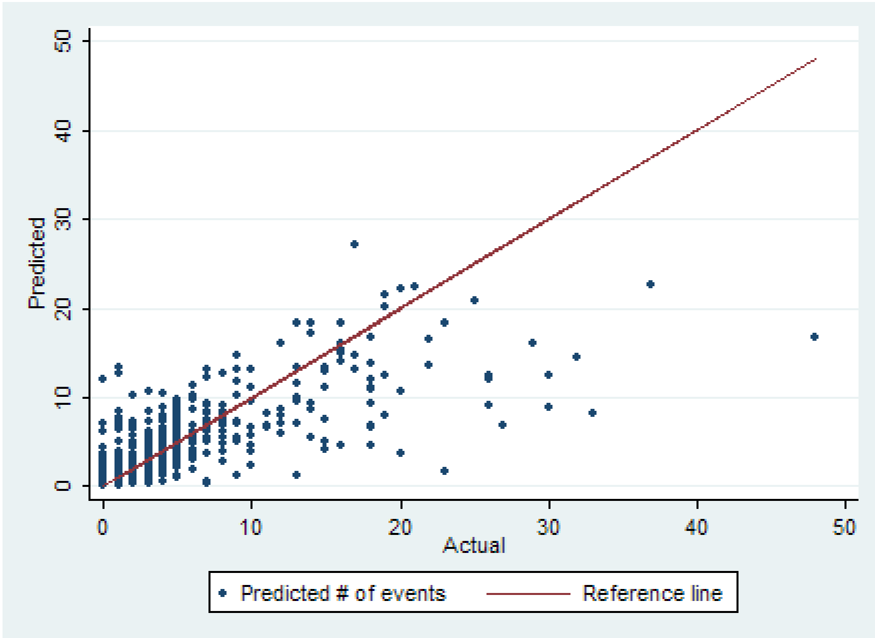


Figure 18: Actual 2004 Distribution Under "Best Case" Assumption

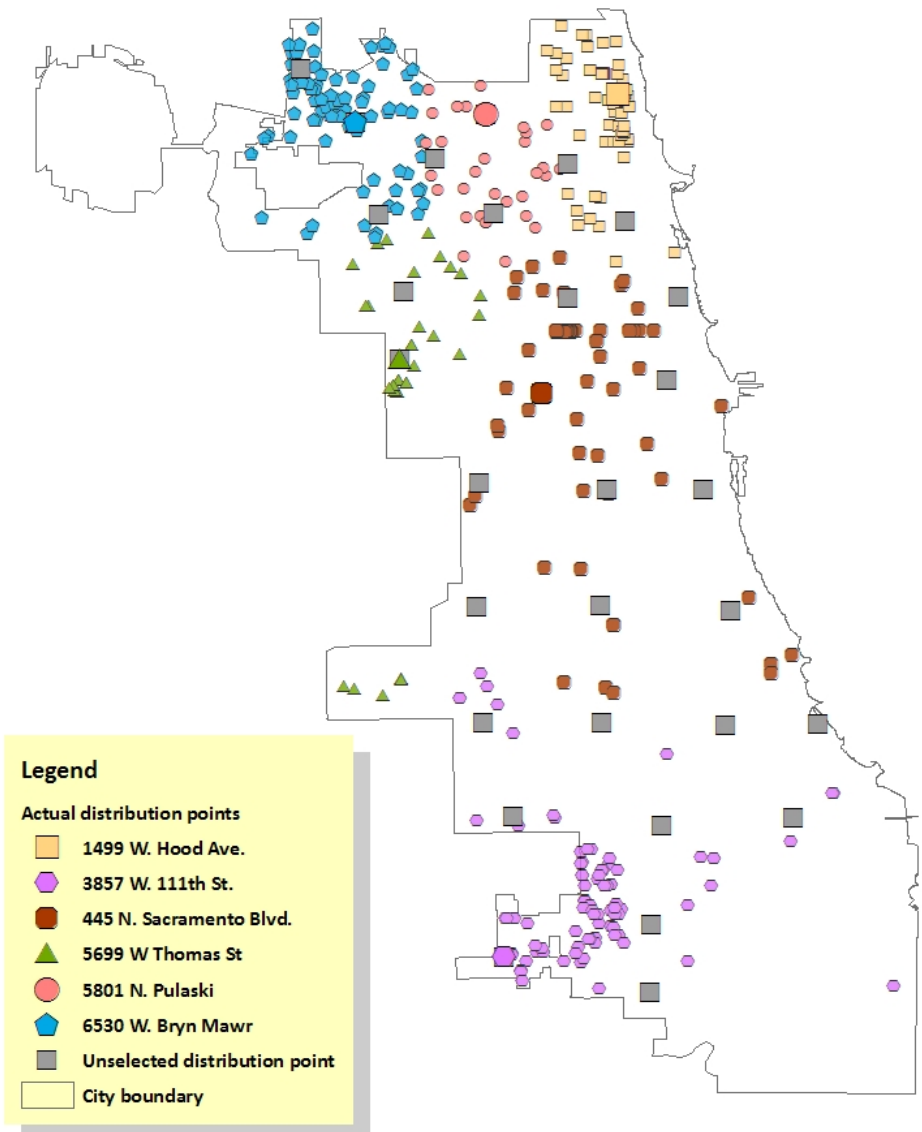
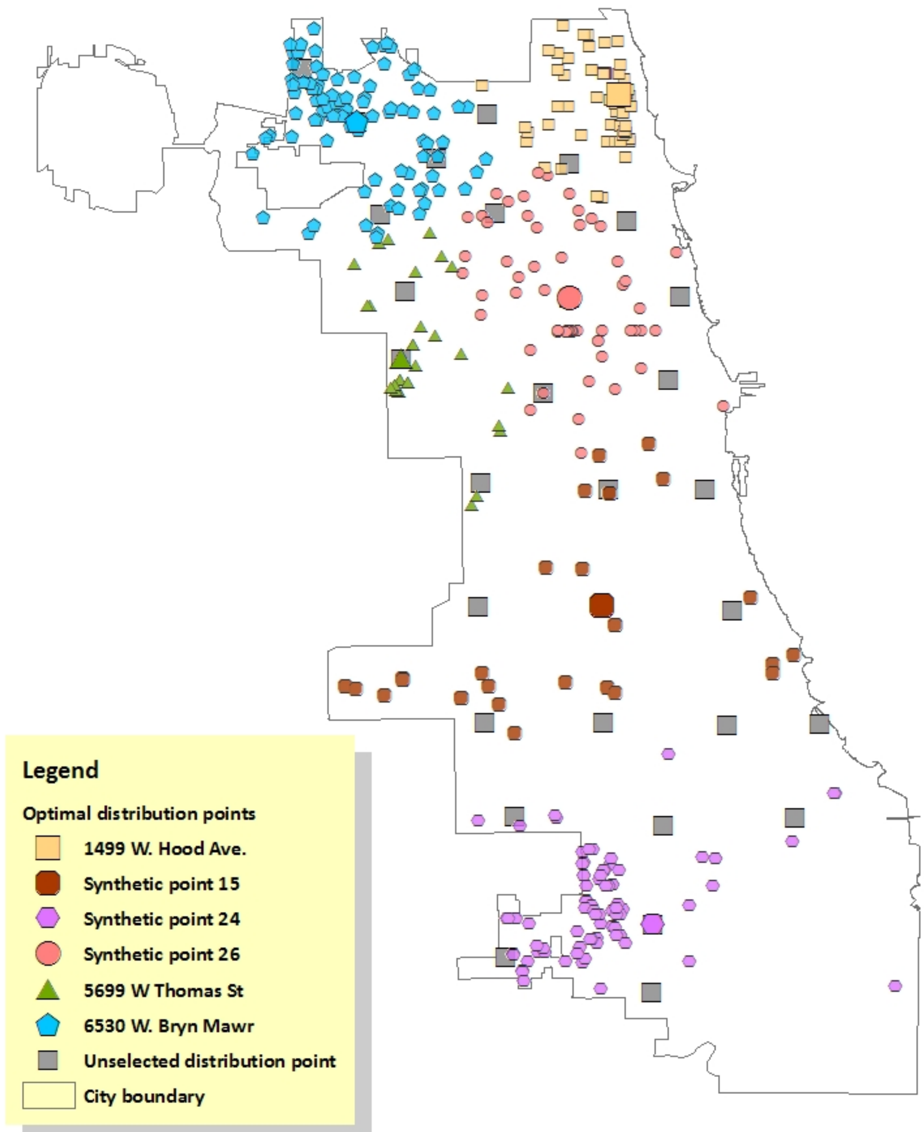


Figure 19: Optimal 2004 Distribution



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